

DESIGN CONSIDERATIONS
OF SUBMARINE POWER LINKS

by

Alexander Robert Swan Wallace B.Sc.

13th May, 1976



ELECTRICAL ENGINEERING DEPARTMENT

SCHOOL OF ENGINEERING SCIENCE

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(GROUP 2: ELECTRONICS AND ELECTRICAL ENGINEERING)

STUDENT HONOURS DISSERTATION

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REF. HD/ 78

MAY 1976

ABSTRACT

The high installation and repair costs incurred in the transfer of electrical power across an expanse of water suggest careful consideration should be given to the choice of the route followed by a submarine cable. The methods of determining the best route, suggested by this dissertation, do not consider unpredictable changes in submarine conditions. The dangers to a submarine cable can never be eliminated, but by correct choice of route these dangers may be minimised. This dissertation is intended to suggest a design procedure for choosing the best of several possible routes suggested by initial consultation of hydrographic charts. The best route at the design stage may be modified slightly after a full investigation of the route is made on site.

The Western Isles of Scotland are considered in this dissertation. Varied bottom conditions and currents present a high degree of flexibility in the choice of routes.

This dissertation attempts to relate the required and permissible current flow to the submarine environment. The tendency of the cable to sink irretrievably into sediment is analysed. The hydrodynamic forces on the cable are related to the cable dimensions and seabed conditions. The tendency of the cable to move under the action of these forces is also analysed. It has been established that the sections of crossings which require protection are the shore ends. Larger cables may be used at the shore ends in order to increase the safety of the link.

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LIST OF SYMBOLS

<u>SYMBOL</u>		<u>UNIT</u>
p	- conductor power loss	W/m
I	- series current $(I_{\text{real}}^2 + I_{\text{reactive}}^2)^{\frac{1}{2}}$	A
R_{DC}	- ohmic resistance/m of one phase of cable	Ω
V	- line voltage	V
ρ	- electrical resistivity	$\Omega \text{ m}$
A	- c.s.a. of copper conductor	m^2
ω	- mains rotational freq. $\times 100\pi$	rad/sec
n	- no. of conductors/cable	
c	- axial distance of each conductor from centre of cable	m
G	- electrical conductance	$\Omega^{-1} \text{ m}$
Cap.	- shunt capacitance	$\mu\text{F/m}$
V_{phase}	- phase voltage	V
ϕ	- dielectric loss angle	rad
T	- conductor temperature	$^{\circ}\text{C}$
K	- thermal resistivity	$\frac{\text{W}}{\text{m}^{\circ}\text{C}}$
D	- diameter	m
d	- diameter of conductor	m
C	- thermal conductivity	$\frac{\text{W}}{\text{m}^{\circ}\text{C}}$
L	- laid depth of cable	m
h	- convection constant	$\frac{\text{W}}{\text{m}^2 \text{ } ^{\circ}\text{C}}$
θ_s	- temperature difference	$^{\circ}\text{C}$
P	- internal fluid pressure	N/m^2
Vol.	- volume of internal fluid	m^3
ρ_g	- density of internal fluid	kg/m^3
v_D	- velocity of water at depth D	m/s
μ	- coefficient of sliding friction	
ρ_w	- density of seawater	kg/m^3

<u>SYMBOL</u>		<u>UNIT</u>
v_s	- velocity of water on surface	m/s
C_D	- drag coefficient of cable on flowing water	
F	- hydrodynamic force	N
R	- normal reaction	N
S	- dielectric loss angle	rad

CHAPTER 1

1. INTRODUCTION

Historically, the transmission of information preceded that of energy. Two dates are especially important in the early history of submarine cable laying. In 1858 the first Atlantic telegraph cable was laid, which unfortunately failed after twenty days use. In 1866, the first successful transatlantic cable was commissioned. The transfer of energy by submarine cable was not effected until the beginning of the 20th century since, prior to that time, cable making and cable laying technology limited the practicality of energy transmission. At that time rotating machines were available to generate electrical energy from mechanical energy. In spite of the difficulties arising in arranging efficient commutation these first machines were used to produce direct current. Direct current was difficult to distribute economically; a constant current distribution required overinsulation of the receiving equipment, whereas a constant voltage distribution entailed oversize conductors. For a given power, there existed an optimum economical relationship between voltage and current. This relationship made it necessary to reduce the voltage as the load was divided among smaller and smaller groups of consumers. The introduction of the transformer by Gaulard and Gibbs and the advent of a.c. generation allowed economical distribution of energy.

The development of electricity supplies in the North of Scotland followed this pattern (1). In 1890 a twin wire d.c. distribution system was established at Fort Augustus. Transmission was at 130 volts. From 1890 until 1903 all the local generation and supply was direct current. In 1903 a three phase a.c. system was commissioned at

Strathpeffer, with distribution at 415 volts. Until 1922 isolated development of supplies had taken place all over Scotland. It was then realised that an increase in reliability could be obtained by linking the systems together to form small grid systems. Local generation spread throughout Scotland faster than the grids could be extended. This meant that only in more recent years has the grid system, in its present form, been extended to the more remote parts of the mainland of Scotland.

Many of the islands off the Scottish mainland are still not connected to the grid system. These islands have local generating stations, mostly based on diesel generation. With increasing oil prices this form of supply may prove to be uneconomical. Each community being isolated electrically from the national grid system has a decreased reliability of supply. It is obvious that these communities should be tied into the grid system wherever possible. This interconnection of islands to the grid is realised using submarine power cables.

The unit-length cost of installing submarine power links is very high, for a short 33 kV cable the installed cost is £32/metre. The cost of a repair on a faulted cable costs on average, 25% of the installation cost, thus for an 8 km link, the repair costs might be £64,000. The capital cost of such a link would be £256,000. The necessity for optimal design and routing becomes obvious. A 1% saving in capital costs, by better design or better choice of route, would save £2,560. A more carefully chosen route might lessen the chances of cable failure and might save £64,000.

This dissertation is a study of the procedures involved in optimising the route along which such a submarine power cable might be laid in order to extend the grid system to an isolated community, or to reinforce an existing supply.

1.1 A.C. AND D.C. SUBMARINE POWER LINKS

The type of supply to an island is a choice now open to the designer. With the development of a.c. to d.c. converters it is possible to supply energy with either alternating or direct current. The grid system can remain alternating, but direct current submarine transmission of power can take place. Each type of transmission has its own advantages and disadvantages, some of which are now mentioned.

In an a.c. submarine cable the shunt capacitance has to be charged and discharged every cycle. The reactive current can be a large proportion of the current carrying capacity of the cable, particularly in long cables supplying small loads. The heating losses due to current flow in the series resistance of the cable may cause excessive local heating of the cable where the thermal conductivity of the surroundings falls, such as at shore ends. A.C. cables also tend to be less robust because of their three phase construction, as shown in figure 2 on page 7, than d.c. cables. This means that laying and positioning must be much more carefully carried out with a.c. cables. One advantage of a.c. transmission is that circuit isolation can be arranged more easily than with d.c. transmission since in a.c. transmission the current passes through a zero every $1/100$ sec. Fault conditions are therefore likely to be interrupted more quickly and easily.

In a d.c. submarine cable (17) the shunt capacitance is charged in the turn-on transient and remains so until isolation or reversal of power flow takes place. The losses in the cable are dependent on its series resistance and are very much smaller than those in an a.c. cable, of similar length and for equivalent power flow. The limitation on distance, using d.c. cables is therefore much less severe. Where system reinforcement is taking place, either internationally, or locally the power transmitted by the d.c. link is independent of the phase, frequency,

4.

and voltage level of the two a.c. systems. Variations in the terminal voltages of the grids do not affect the power transfer. The current in the d.c. link is controlled by the converter stations, so grid faults on the a.c. sides do not result in additional current flow in the link. One of the main savings with d.c. submarine links is the fact that only two single core cables are necessary. Normally a double circuit arrangement is used with two conductors each using the sea as a return path. If the two conductors are of opposite polarity, under balanced conditions no return current flows through the sea. If one cable should fault the other can continue transmitting power, using the sea as a return path. With this system there is a considerable saving compared with an equivalent a.c. double circuit link, where six conductors are required. Further saving exists with d.c. transmission. For a given transfer of power, the a.c. cable has to be designed to withstand the peak voltage whereas the d.c. cable can transfer the same power at $1/\sqrt{2}$ times the a.c. peak voltage. The main disadvantage with d.c. transmission to small isolated communities is the high capital cost of terminal equipment. Additional disadvantages include the necessity of reactive power generation at the end of the link, since no reactive power flows in the link.

It thus becomes obvious that the type of transmission which is to be installed presents a difficult choice. The general trends in practice appear to be that supplying small island communities close to the source of supply a.c. is a better means of transmission. Where larger, more remote islands are to be linked into a grid to provide reinforcement of their local generation, d.c. is a better means of supply. Aside from the technical considerations already mentioned, the high capital cost of supplying a small community by a d.c. link cannot be economically justified. In the case of the Western Isles in Scotland, the cost of a.c. installations has to be recovered by increased tariffs on the mainland.

1.2 ECONOMICS

For the purposes of optimisation of economy another technical/economic factor may be considered. As the community becomes more remote from the mainland and the proposed link becomes longer, the installation costs will increase. The probability of cables failing increases with submerged length, therefore the maintenance and repair costs might be expected to increase with the length of link. A breakpoint must exist when it becomes less economical to install a link than to install or reinforce local generation.

In this investigation it is assumed that a submarine link is the preferable means of supply. Local generation will only be indicated as a final alternative in some case studies.

1.3 EQUIPMENT CURRENTLY USED IN ESTABLISHING LINKS

1.4.1 CABLES

There are several types of cables manufactured, each particularly suited to one type of transmission (14).

(a) Solid Cable

Solid cables are laid up as shown in Figure 1 on page 7. Cables such as these are used to transmit at voltages of 250 kV. This type of cable can be made in long lengths, for instance one cable factory in France is capable of producing 40 km lengths of cable. The simplicity of this cable also facilitates jointing and repair work at sea. These cables are primarily produced for transmitting direct current, but three such cables can be used to transmit three-phase alternating current. Where deeper water may be encountered, solid type cable is given an oval shape. The lead sheath must be reinforced elastically so that it can be

deformed under the internal pressure built up by the heating cycle, and restored to its original dimensions by the external water pressure. The formation of voids in the insulating material around the cable is limited with this design.

(b) Oil-Filled Cable

An example of an oil-filled cable shown in Figure 2 on page 7 . A typical oil pressure within the oil duct might be 1500 kN/m^2 (220 p.s.i.). The oil pressure must be such that a positive pressure differential exists between the oil duct and the surrounding water, at all points along the submerged cable. The advantage in this system is that positive pressure prevents ingress of water in the event of minor sheath failure. The oil used must be sufficiently viscous to prevent migration at the highest temperatures encountered under load or fault conditions, yet still remain flexible at the lowest winter temperature encountered. Cable of the type shown in reference 18 was used in the Long Island sound Interconnection and operated at 138 kV, 300 MVA. Seven cables made up two three phase circuits with one spare. The main disadvantage of this type of oil-filled cable is the necessity to feed oil at different points along the cable to compensate for pressure drop. One solution to this problem is that used in the Konti-Skan d.c. project in Scandinavia (19). Self-compensating Mollerhoj cable was used, where no longitudinal motion of oil or pressure variation takes place. These cables are bipolar as shown in Figure 4 on page 8 . Expansion of the oil on heating results in the flat sides being elastically deformed like uniformly loaded beams. On cooling the elastic forces restore the shape of the cable and prevent void formation. These cables are obviously heavier and more difficult to lay than single core cables. The Konti-Skan scheme operates at 250 kV, 1050 A d.c.

FIGURE 1 250 kV, 625mm², SOLID CABLE

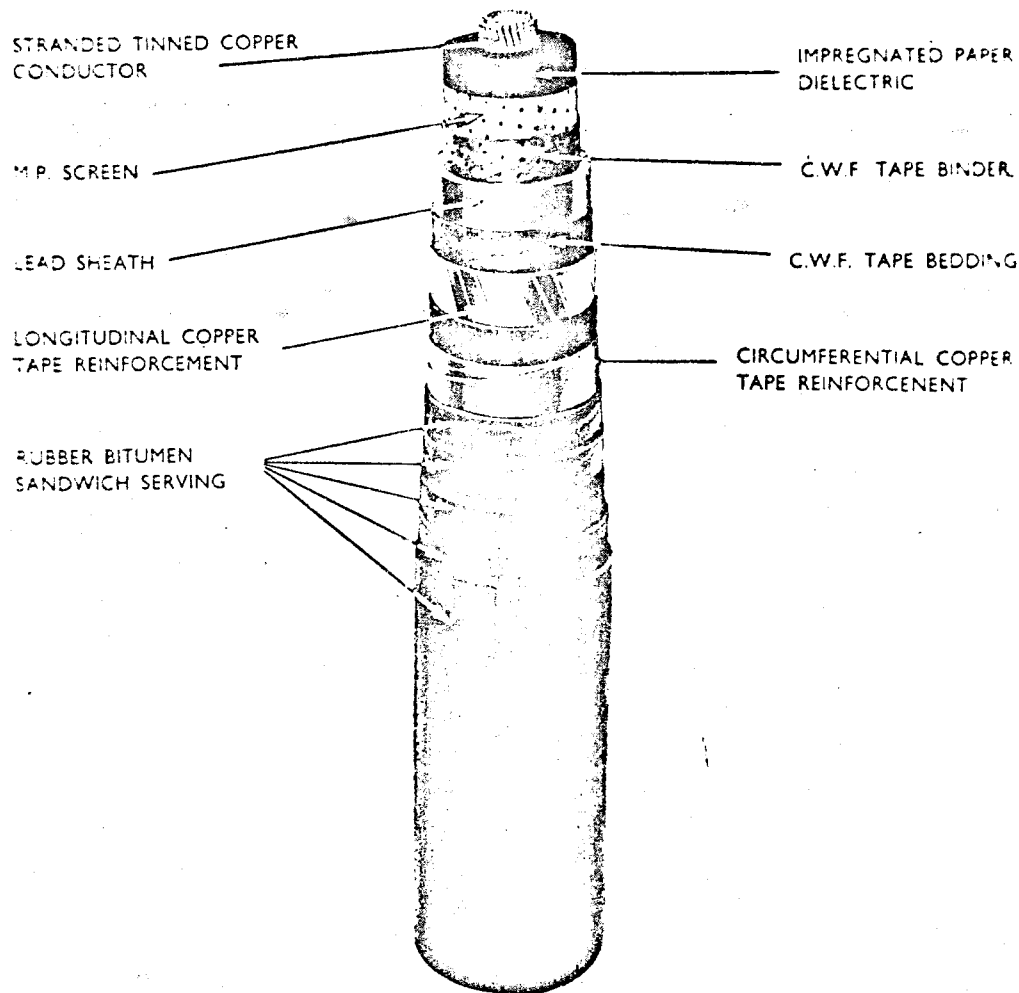
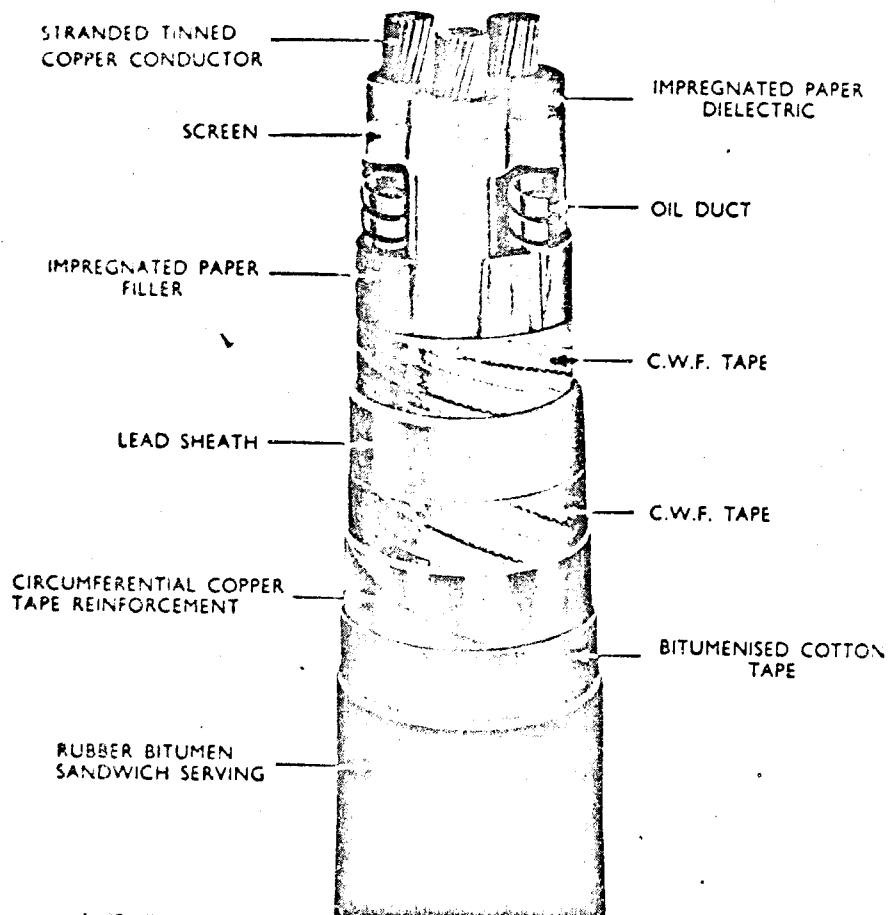


FIGURE 2 66kV, 3 CORE, OIL-FILLED CABLE



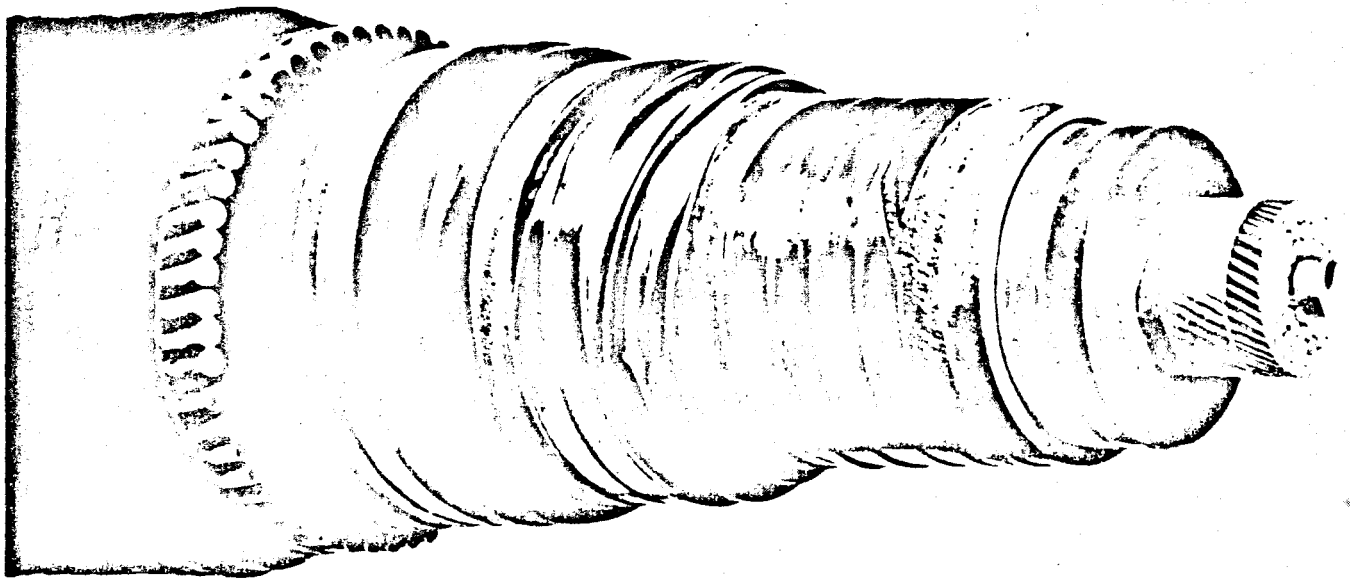
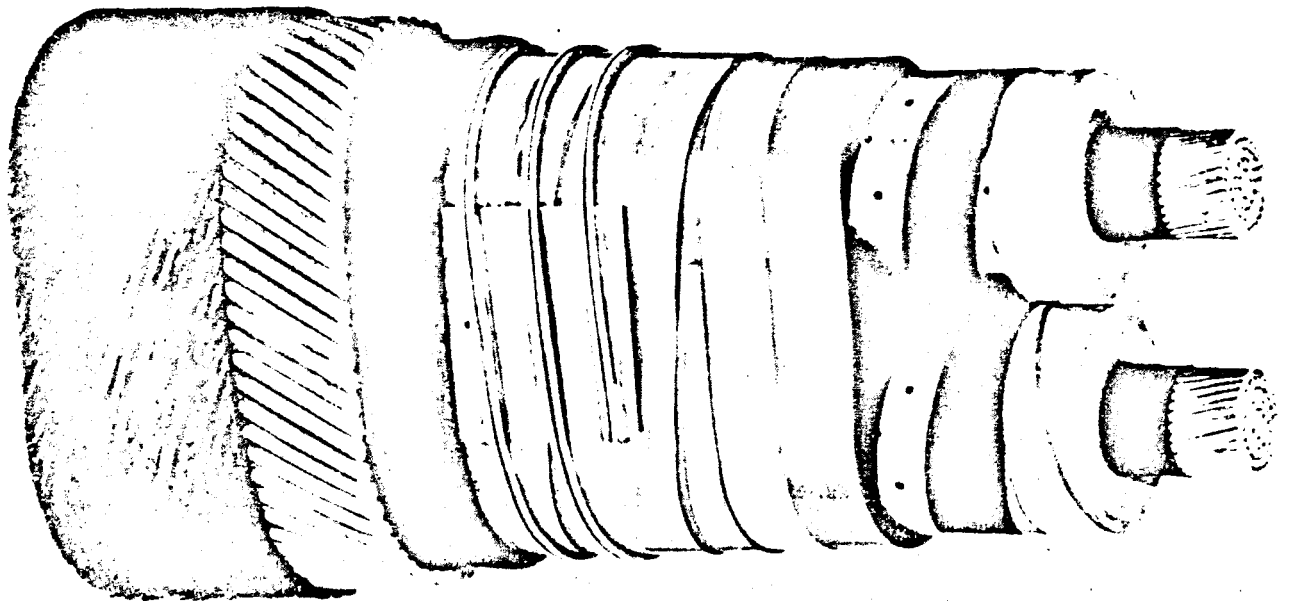


FIGURE 4

MOLLERHOJ CABLE



(c) Gas-Filled Cable

Gas-filled cables are maintained at a positive pressure differential everywhere along the submerged length of the cable. Voids are prevented since the insulation is under internal pressure. Ingress of water is prevented under rupture of the insulation, by the positive pressure differential. The only trouble encountered with this type of cable is gas ducts becoming clogged with loosened insulating compound. The resulting pressure drop allows insulation deformation and a corresponding drop in the withstand level of the cable. The withstand level of the cable is that conductor-sheath voltage which initiates insulation failure by ionisation of the insulating material. Gas-filled d.c. cables were used in the Cook Strait Project (20), linking the North and South Islands of New Zealand. These cables, as shown in Figure 3 on page 8, operate at ± 250 kV 600 A d.c. and span a distance of 17 nautical miles.

(d) Extruded Polythene Cables

Considerable work has been carried out on the suitability of extruded polythene cables for high voltage d.c. transmission. The lightness and resistance to abrasion of the polythene suggests that such cables would be ideal in submarine applications. Experience has shown, however, that unavoidable voids and irregularities in the polythene can lead to early failure of the cable.

1.4.2 CABLE LAYING EQUIPMENT

One type of cables ship used at present is shown in the photograph in Figure 5 on page 10. Cables ships such as the M.V. Insistence, shown are usually converted bulk carriers so chosen because of their large, unobstructed holds. In order to minimise the number of undersea joints the practice is to manufacture cables in as long lengths as possible. In the Cook Strait Project the cables were each 40 km long.

FIGURE 5 M.V. INSISTENCE

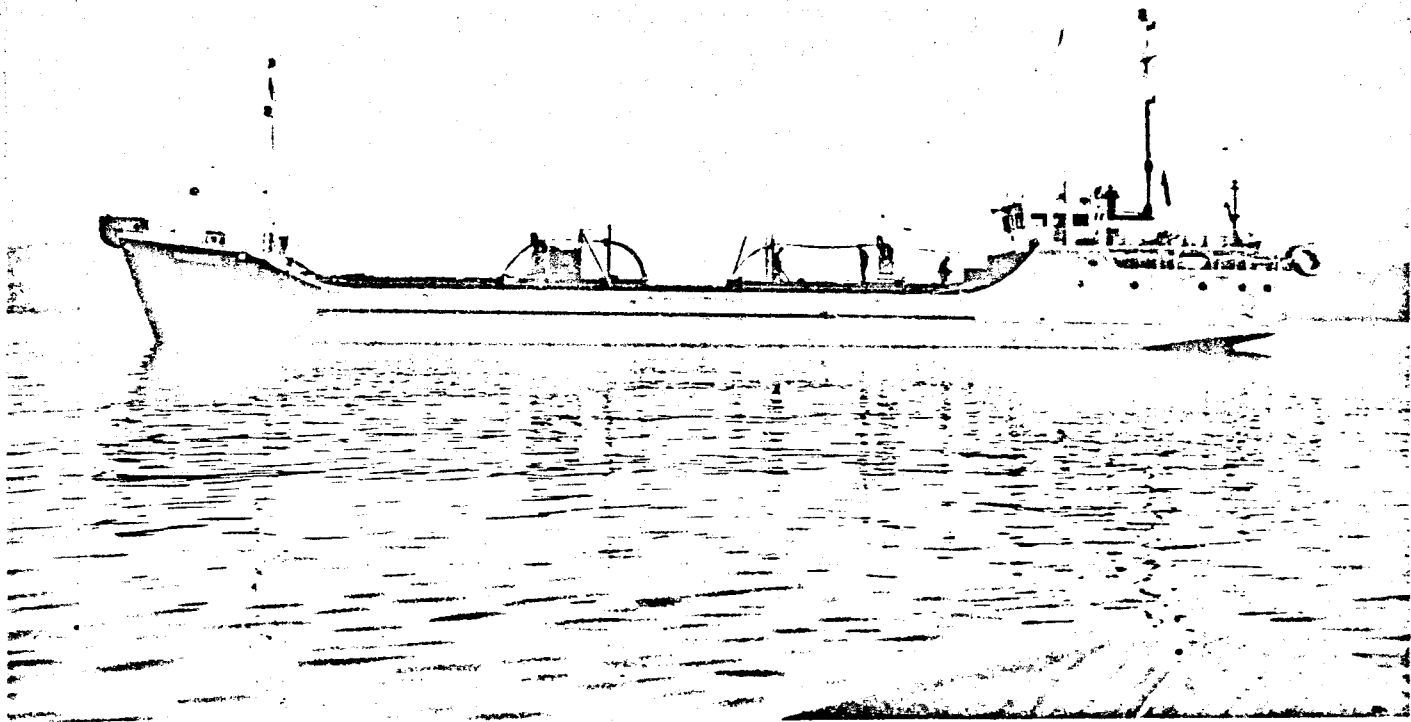
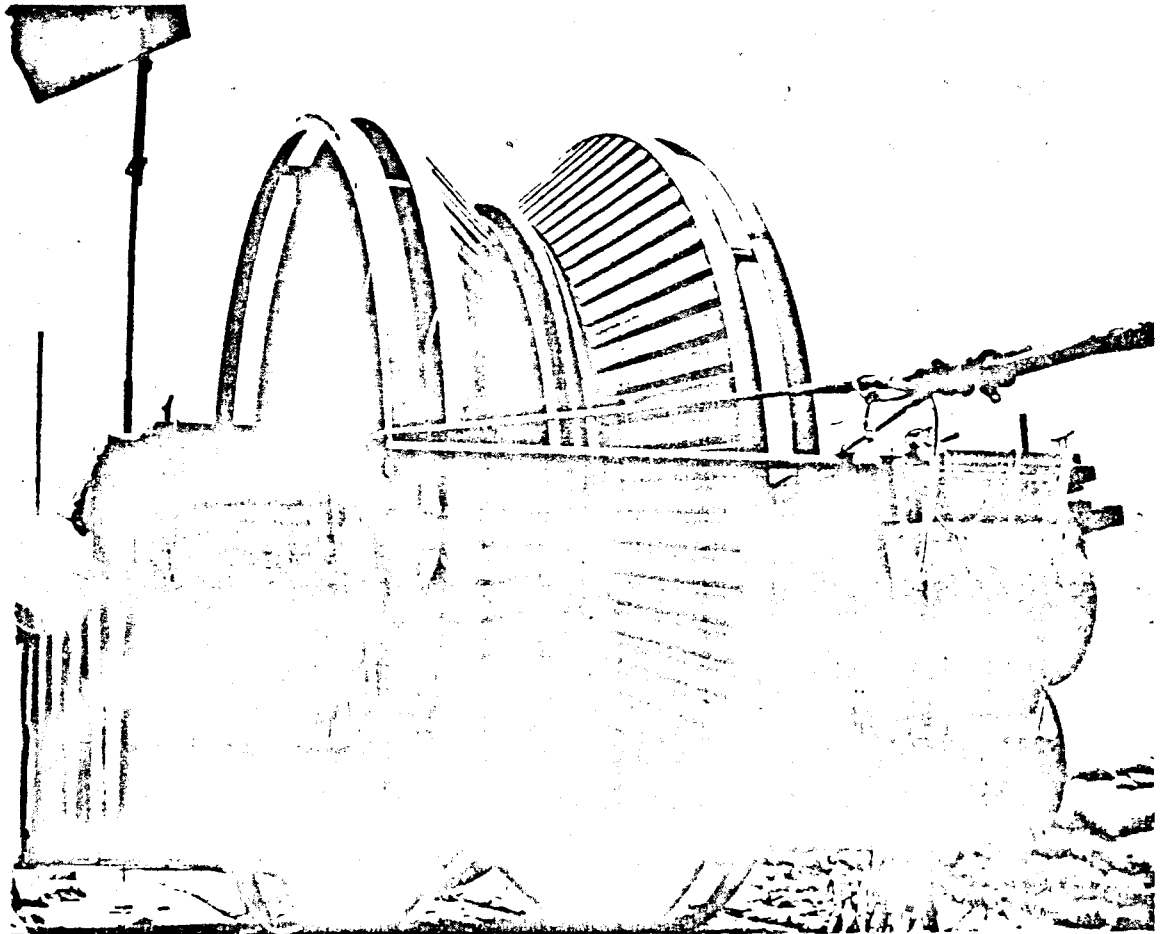


FIGURE 6 FLOATING HEAD



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In order to store 40 km of cable coiled down into 16 m coils, large holds are necessary. The cables are pulled from the holds by winches and fed into brakes. From the brakes the cable is passed over a specially constructed stern apron and lowered into the sea. The brakes are used to regulate the tension in the cable as it is being laid and thus prevent kinking or stretching of the armouring. Fore and aft anchors on both the port and starboard sides are usual equipment, for occasions when the ship has to be moved directly port or starboard. Jointing equipment must be provided on board, where a cable has to be installed in more than one length. The extra navigational equipment necessary includes echo sounding equipment to continuously monitor the laying depth and bottom conditions, and radio position equipment to continuously monitor the velocity and position of the ship. Up-to-date accurate charts of the submarine terrain are required before use is made of the electronic aids. The cables ship may be assisted by smaller tugs and support vessels at some points in a laying operation. A floating head device may also be used to land the finishing ends of the cable, as shown in Figure 6 on page 10 .

CHAPTER 2

2. CURRENT PRACTICE

2.1 INITIAL FACTORS INFLUENCING THE CHOICE OF ROUTE

When the two extremities of the existing electrical systems have been identified, or the extremity of an existing grid and the load centre of the isolated community have been located, usually an overland section of cable or spur line will have to be installed. This introduces some flexibility into the choice of landing points for the cable. The optimal submarine route may terminate remotely from the ends of the shortest, straight line, link. The landing points are therefore chosen on their suitability to cable landing, rather than geographical nearness. Generally a flat, sandy beach sheltered from high seas and strong currents is desirable. The landing points are preferably secluded, and off regular shipping lanes and trawling grounds, to prevent man-made damage to the cables.

Having established several landing points, the submarine routes between sets of two points must be optimised. Again, the most direct route is not necessarily optimal. Deviation from the direct route must be considered, to avoid sea bed conditions which may lead to cable failure. Topographic studies (16) form the basis for initial route selection. A series of depth profiles and bottom characteristics are used to determine the best cable route.

A route is chosen on the following basis:

(a) RELIEF. High sea bed gradients are avoided, since both laying and recovery are made more difficult. Submarine canyons and rises are avoided in order that the cables are not subjected to excess bending.

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(b) BOTTOM CONDITIONS. Jagged and rough bottoms are avoided, since any motion of the cable on such a bottom would result in abrasion and eventual structural failure. Highly sedimented and undulating bottoms are also avoided since a submarine slump or avalanche may occur and the cable may be damaged or broken by the force of the sediment in motion.

A flat, slightly sedimented bottom is often desirable since the cable may be lightly covered by sediment and anchored against movement by sea bottom currents.

(c) CURRENTS. It is usually assumed in the initial investigations that the currents on the sea bed can be taken as small number fractions of the surface currents. In depths of greater than 20 m the bottom current is taken as $\frac{1}{3}$ of the surface current. In depths of 20 m and less the bottom current is taken as $\frac{1}{2}$ the surface current.

There is some doubt as to whether these assumptions are valid in every case. Chapter 6 of this dissertation analyses the types and respective magnitudes of the currents relevant in the initial choice of route.

The estimation of currents is only a design consideration, since before a route is adopted the currents are carefully measured at all points along that route. Routes entailing high transverse currents should be avoided since the current may be sufficiently strong to move the cable on the seabed. Scouring and abrasion of the armour and protective covering are a likely result of such motion. A relationship exists between the weight/unit length and diameter of a cable and the magnitude of current which will just move it for given seabed conditions. Standard practice assumes a coefficient of friction on the seabed of 0.5

This value of coefficient of friction may be too high. Section 5.3 of this dissertation analyses the seabed conditions and the validity of this coefficient of friction. This again is only a design consideration because in practice if a cable is suspected of moving it is anchored periodically with cement filled bags, placed in position by divers.

(d) TEMPERATURE AND PRESSURE. Seabed temperatures must also be noted from charts of the annual temperature variations and drifts. This is necessary to ensure that in operation no localised overheating of the cable results in insulation failure. The flow of generated heat from the cable to the surroundings can be related to the temperature difference between the cable and the surroundings by the thermal conductivities of the intervening materials. If the temperature of the surroundings is lowered, or the thermal conductivity increases, the cable temperature will fall for a given power dissipation in the cable. This has profound implications on the design of the cable route. Immersion in sea water allows the cable to dissipate more heat and consequently operate at lower temperatures, for a given transfer of energy. Alternatively, for the same internal temperatures as established on dry land, greater amounts of power can be dissipated and the submarine section can be overrated.

The exact amount by which the cable can be overrated is the subject of some controversy within the supply authorities. Chapter 3 of this dissertation analyses the steady state power losses in differing surroundings and the amounts by which the cable can be overrated. Current practice is to use larger diameter cable at the shore ends, where the cable is not able to dissipate generated heat easily.

Bottom pressures must also be calculated from the depth profile of a proposed route. The route must be chosen such that the maximum pressure at any point along the installed cable is minimised. This is

necessary to prevent ingress of sea water into the insulation of the cable. The maximum bottom pressure may also indicate the type of transmission (a.c./d.c.) most suitable, according to the type of cable best installed.

Chapter 4 of this dissertation examines the way in which pressure varies and the influence of this pressure variation on the choice of route and supply.

(e) SEISMIC ACTION, MAGNETIC EFFECTS and BIOLOGICAL SAFETY.

Geophysical maps must be inspected to check the stability of a proposed seabed. Seismic action may dislodge accumulations of sediment or outcrops of rock which may damage or break a cable. Seismic faults may occur under the cable and create precipices over which the cable can become abraded and fail as a result.

In the case of d.c. cables shipping lanes must be avoided due to the influence of the generated magnetic fields on ships' magnetic compasses. Where possible, an East-West route should be chosen, in which case the earth's magnetic field and the magnetic field created by the presence of the cables will not interact in such a way as might affect the ships compasses.

Marine life records must be examined to determine if certain types of boring organism, such as the Teredo, are present in the waters into which the cable is going to be laid. Marine boring organisms can puncture the water insulation and result in the ingress of sea water with the insulation failure inevitably following.

(f) WEATHER. Meteorological records must show that it might be reasonable to expect frequent periods of sufficiently calm weather long enough to lay or repair a cable in the site chosen.

When the considerations (a)-(f) have been examined and it still seems feasible to install submarine cables along an optimised route, the route is carefully marked onto a navigation chart of the area and further investigations take place.

2.2 FINAL EXAMINATION OF ROUTE AND LAYING PROCEDURE

Once the cables ship has arrived at the proposed location of the link it will sail along the proposed routes. The route along the seabed will be continuously monitored. An echo sounder will check the depth and bottom density. (The amplitude of an oscilloscope trace indicating the depth, and the dispersion of the trace, the bottom type). The currents along the proposed route are measured and the seabed temperatures noted. If an abnormality or unexpected feature arises during this final check, a diver and camera may be sent down to examine the proposed route. The cables ship also checks its closest safe approach to the land ends of the route in order to determine the procedure for landing the cable.

When the route is finally adopted the laying operation may begin (3).

The cables ship comes as far inshore as is safe and starts paying out cable over the stern as shown in Figure 7 on page 17. The ship is anchored by port and starboard bow and stern anchors and the cable is either floated or winched ashore to the first land end. The cables ship then steams across the proposed route at a rate determined by the laying conditions, as shown in Figure 8 on page 17. As the cables ship moves away from the secured end of the cable the cable is paid out through a bellmouth and through the brakes to the stern apron. From the stern apron the cable is paid into the sea. Depending on the contour of the seabed the rate of paying out cable is adjusted corresponding to the land speed of the ship. The reason for this is to maintain a positive tension in

FIGURE 7 CABLE BEING WINCHED ASHORE

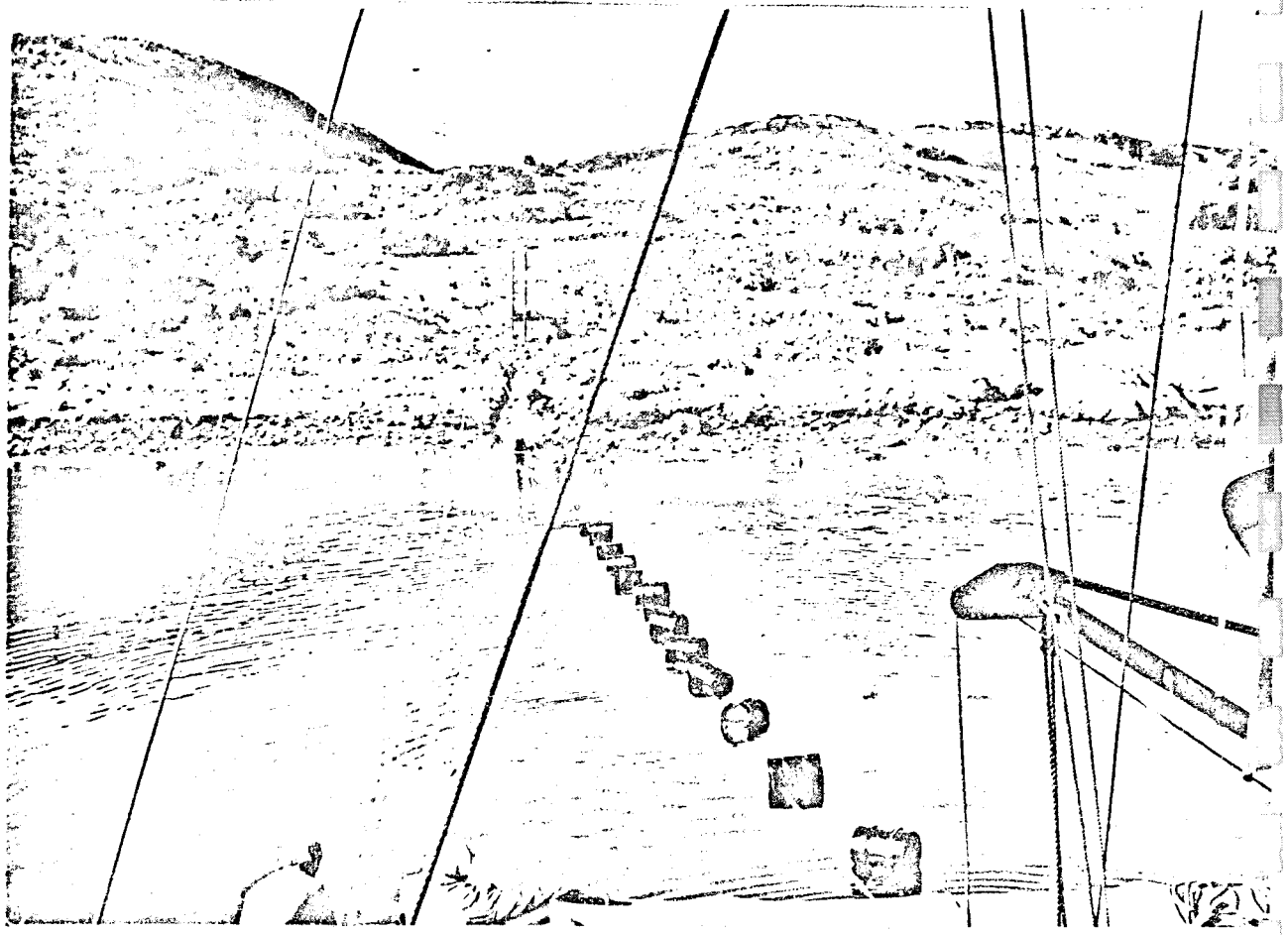


FIGURE 8 LAYING IN PROGRESS

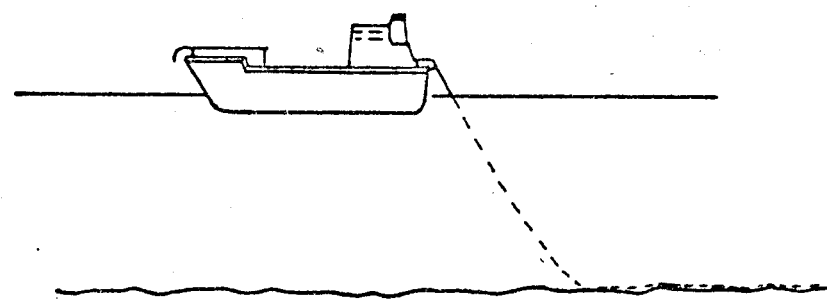
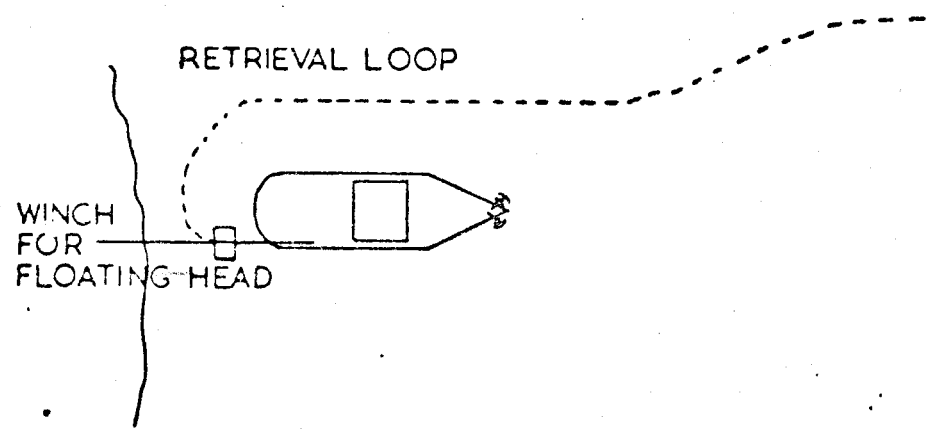


FIGURE 9 LANDING



the cable under all conditions until it reaches the seabed where the internal tension should fall to zero. Excess tension during laying causes deformation of armouring and insulation failure. Insufficient tension causes kinking of the cable and insulation failure

The cables ship thus arrives at the other end of the route bow first with the cable ready for paying out to the shore. This is accomplished by paying out a loop which is either floated, or winched straight and hence reaches the shore, as shown in Figure 9 on page 17. The two ends of the cable are now secure at either end of the route and the cables ship is disengaged.

Only after electrical and mechanical testing of the cables, and shore end terminal stations, can the link be commissioned.

2.3 PROBLEMS ARISING IN CURRENT PRACTICE OF ROUTE OPTIMISATION

In the previous few pages several problems in the design of cable routes have become apparent. Whilst the writer of this dissertation appreciates that the final inspection of a route and the laying of a cable are very much on site problems, there are several considerations which may be investigated prior to sending a cables ship to the actual location. Provided up to date hydrographic, topographic, and geophysical information is available feasible routes between two specified land points separated by sea and land can be determined. The advantages of these types of paper studies are (i) minimal costs are incurred in the process of obtaining an appreciation of the feasibility of installing a link, (ii) several alternative routes become apparent during the determination of the possible routes to be used. If an unexpected problem occurs on site and the first route has to be abandoned, several others are readily

at hand and can be quickly investigated by the cableship.

The remainder of this dissertation is devoted to the analysis of the problems which affect the feasibility of installing submarine power links. A design procedure is evolved in the latter part of this dissertation which can be applied to any proposed electrification or reinforcement of supply on an island. The problems analysed are:

Chapter 3. Temperature Variation and Cable Rating.

Chapter 4. Pressure Variation along Routes.

Chapter 5. Bottom Conditions.

Chapter 6. Subsurface Currents and Force on Cable on Seabed.

The design procedure is tested on several already installed links, and used to determine the feasibility of other links in section 7.6 on page 71.

CHAPTER 3

3. HEAT FLOW FROM POWER CABLES ON THE SEA BED AND CURRENT CARRYING CAPACITY

In section 2.1(d) on page 14 some mention was made of the effect of immersing power cables in cold media such as the sea. Due to the increased thermal conductance and lower surrounding temperature the heat flow from the cable increases. For a constant rate of generation of heat the conductor temperatures fall. For specified maximum conductor temperatures the generation of heat within the cable can be increased. Cables can thus be up-rated safely in submarine environments. Submarine power cables are always connected to the dry land station equipment by lengths of cable not always submerged, known as shore ends. The external shore end thermal properties are better to be treated as dry land properties. Since the power flows through both the shore ends and through the submarine cable, the limiting conditions on power transfer are dictated by the shore ends. The submarine cable can, however, be installed of a lower current rating.

This chapter examines the mechanism of heat transfer in both the submarine and dry land environments and relates the two to the current ratings of cables required to transmit power to an isolated load securely.

3.1 GENERATION OF HEAT (8)

The rate of generation of heat in a given cable is the product of the number of conductors and the ohmic loss in each. Ohmic losses due to induced currents in the sheathing also occur.

3.1.1 CONDUCTOR LOSS

Conductor losses are given by

$$P = I^2 R \quad (3.1a)$$

Where I is the current flowing in each conductor and R is a combined resistance term, summing the following resistances and equivalent resistances.

$$R_{AC} = R_{DC}(1 + A_1 + A_2) \quad (3.1b)$$

R_{AC}/R_{DC} = alternating/direct current resistances

$A_1 R_{DC}$ = increased resistance due to skin effect producing a non uniform current distribution

$A_2 R_{DC}$ = increased resistance due to proximity of other conductors

The d.c. resistance of the conductor can be calculated from the expression

$$R_{DC} = \rho \frac{l}{A} = \rho/A \Omega/m \quad (3.1c)$$

R_{DC} can be taken from records on the cables concerned. The skin effect factor A_1 can be calculated at mains frequency from the formula

$$A_1 = F(x) \text{ where } x = \frac{4\omega}{R \times 10^7} \quad \text{If } R/m \text{ is known} \quad (3.1d)$$

$$= \frac{4\omega A}{\rho \times 10^7} \quad \text{If geometry of cable is known}$$

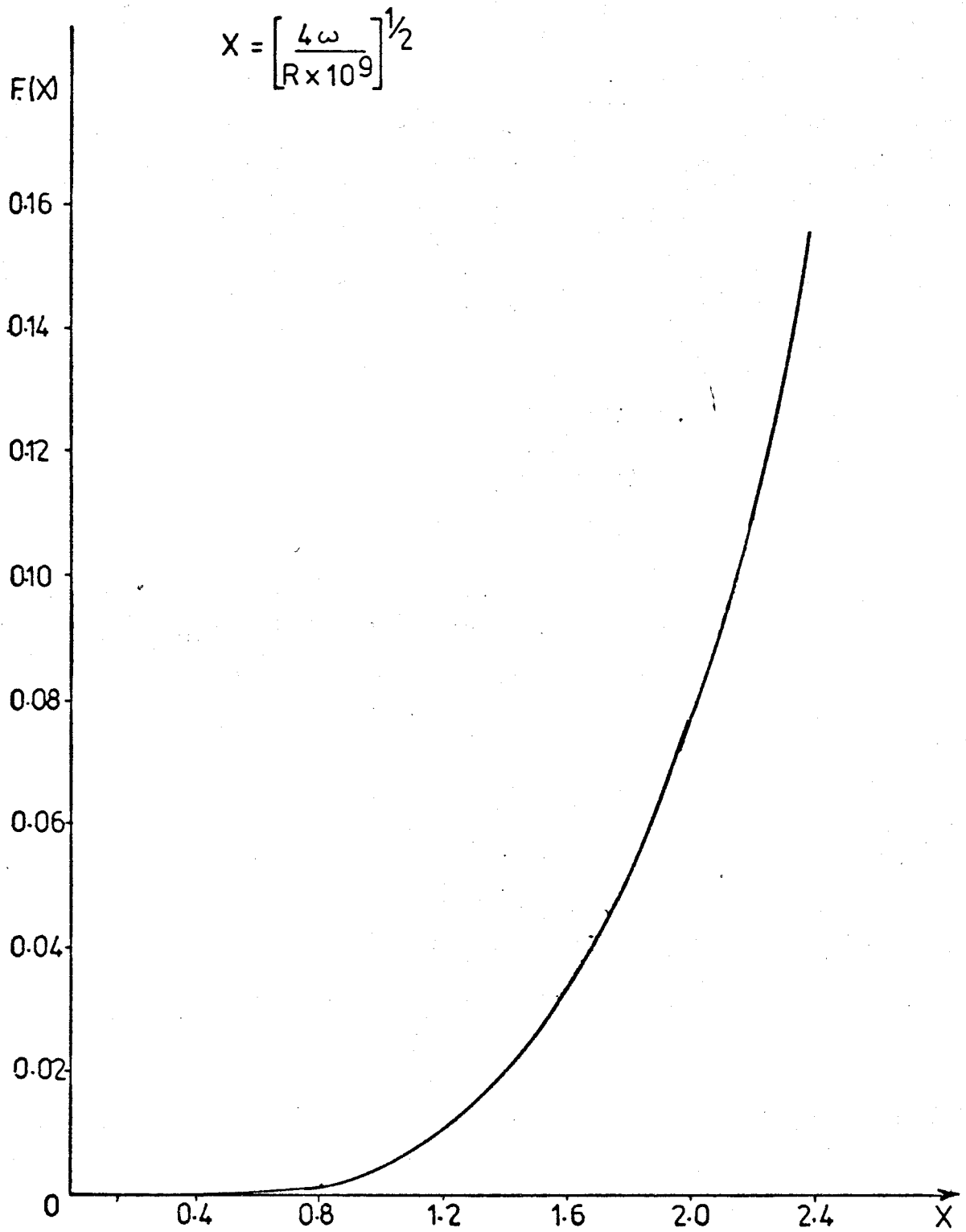
Here $\omega = 2\pi \cdot 50 = 314$

The function $F(x)$ is plotted against x in Figure 10 on page 22.

From this graph A_1 can be read once x is known.

The proximity factor A_2 to account for the effect of the other conductors within a cable is largely dependent on the conductor diameter/

FIGURE 10 VARIATION OF SKIN EFFECT RESISTANCE AND
D.C. RESISTANCE



spacing ratio.

$$\begin{aligned}
 A_2 &= \left(\frac{2r}{s}\right)^2 A_1 \text{ for single phase cables} \\
 &= 1.5 \left(\frac{2r}{s}\right)^2 A_1 \text{ for three phase cables}
 \end{aligned}
 \tag{3.1e}$$

Thus the total conductor losses can be expressed as

$$\begin{aligned}
 P_1 &= nI^2 R_{DC} \text{ for D.C. cable} \\
 P_1 &= nI^2 R_{DC} (1 + A_1 + A_2) \text{ for A.C. cables}
 \end{aligned}
 \tag{3.1f}$$

N.B. $(A_1 + A_2) R_{DC} \equiv$ A.C. resistance

3.1.2 SHEATH LOSS

It is usual to express the losses in the sheath as a fraction λ of the conductor losses. In 3 core cables

$$\lambda = \frac{16 G_{\text{CONDUCTOR}} m^2 c^2}{5 G_{\text{SHEATH}} (1 + m^2) r_L^2}
 \tag{3.1g}$$

c = axial distance of each conductor from centre of cable

$m = \omega G_{\text{SHEATH}} \times 10^{-7}$ (G_{SHEATH} in $\frac{1}{\Omega m}$)

r_L = radius of sheath

3.1.3 ARMOUR LOSS

The armour loss is assumed to be 0.08 of the conductor loss

3.1.4 DIELECTRIC LOSS

The dielectric loss in a three phase cable is given by

$$\omega CV^2 \tan \delta \cdot 10^{-4} \text{ Watts/m} \quad (3.1h)$$

where

V = phase voltage (volts)

C = capacitance to neutral ($\mu\text{F/m}$)

δ = dielectric loss angle at operating temperatures

3.1.5 TOTAL HEAT GENERATED IN CABLE (8)

The total rate of heat generation in the cable can be expressed as the sum of the four rates of heat generation in sections 3.1.1 - 3.1.4.

$$P = \text{Conductor Loss} + \text{Sheath Loss} + \text{Armour Loss} + \text{Dielectric Loss}$$

$$p = (1.08 + \lambda) \text{ conductor Loss} + \text{Dielectric Loss} \quad (3.1i)$$

Thus rate of generation of heat can be related to the thermal conductance of the cable - surroundings and the temperature difference, as shown in section 3.3. on page 28 by the equation

$$P_{\text{LOSS}} = C_{\text{TOTAL}} \Delta T$$

C_{TOTAL} is the total thermal conductance of the thermal circuit between the source of heat and the infinite sink at 0°C . The thermal conductances in this circuit include the thermal conductance of the ground/sea and must therefore be included.

3.2 THERMAL CONDUCTIVITY OF SURROUNDINGS

The heat path between the conductors and the sink includes the following conductances in turn

insulation → metallic sheath → bedding → armour serving $\begin{matrix} \nearrow \text{sea} \\ \searrow \text{air} \end{matrix}$

The thermal conductances of the metallic parts of this circuit are so high that they may be neglected. The conductances of importance now become

insulation → (bedding & serving) $\begin{matrix} \nearrow \text{sea} \\ \searrow \text{ground} \\ \searrow \text{air} \end{matrix}$

3.2.1 THERMAL CONDUCTANCE OF INSULATION

The simplest non geometric approximation for a 3 phase cable is to assume the single phase conductance.

$$C_1 = \frac{2\pi}{K} \frac{1}{\log_e(D_i/d)} \frac{W}{\theta_c} \tag{3.2a}$$

K = thermal resistivity of insulation $\frac{\theta_{cm}}{W}$

D_i = dia. of insulation

d = dia. of conductor

For solid cable $K = 5.5 \frac{\theta_{cm}}{W}$
Impregnated Pressure
Cable

For oil filled cable $K = 4.5 \frac{\theta_{cm}}{W}$

3.2.2 THERMAL CONDUCTANCE OF ARMOURING

The thermal conductance of the cable protection can be taken as

$$C_2 = \frac{2\pi}{K_1} \log_e \left[\frac{\text{Dia. of cable} + \text{Dia. of armour} - \text{Thickness of armour}}{\text{Dia. of cable} - \text{Dia. of armour} + \text{Thickness of armour}} \right] \frac{W}{^\circ C} \quad (3.2b)$$

3.2.3 THERMAL CONDUCTANCE OF SUBMARINE ENVIRONMENT

The thermal conductance of the seawater surrounding a power cable can be taken as temperature independent at

$$C_3 = 2\pi C_{\text{sea}} \log_e \left(\frac{r_e - 2L}{r_e} \right) \frac{W}{^\circ C} \quad (3.2c)$$

$$C_{\text{sea}} = \text{Thermal conductivity of sea} \quad \frac{W}{m \cdot ^\circ C}$$

$$L = \text{depth to cable axis (m)}$$

$$r_e = \text{radius of cable (m)}$$

C_{sea} can be taken as constant at $1.42 \frac{W}{m \cdot ^\circ C}$ and the thermal conductance becomes a function of the depth of water in which the cable is laid.

3.2.4 THERMAL CONDUCTANCE OF AIR

The thermal conductance of the air surrounding a cable has to be calculated once the power flow from the cable is calculated.

The total dissipation from the 1 m of cable in air can be approximated by

$$\pi D_e h \theta_s^{5/4} \text{ Watts} \quad (3.2d)$$

where

D_e = diameter of cable (m)

θ_s = temperature difference between cable surface and the surrounding air ($^{\circ}\text{C}$)

h = convection, conduction and radiation constant, typically $2.8 \frac{\text{W}}{\text{m}^2 \cdot ^{\circ}\text{C}}$ for 0.1 m cable.

The external thermal conductance is now

$$C_4 = \pi d_e h \theta_s^{5/4} \frac{\text{W}}{^{\circ}\text{C}}$$

The flow of heat is known and can be equated for the case of the cable to air and within the cable

$$\text{i.e. } (1 + \lambda)(\theta - \theta_s) \left(\frac{1}{C_1} + \frac{1}{C_2} \right)^{-1} = \pi d_e h \theta_s^{5/4} \quad (3.2e)$$

therefore θ_s can be calculated

θ_s can be used to calculate C_4

3.2.5 TOTAL THERMAL CONDUCTANCE

For a cable in either seawater or air, the thermal conductance can be calculated by summing the conductances in the thermal circuit

$$\text{In seawater} \quad \frac{1}{C_{\text{TOTAL}}} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} \quad (3.2f)$$

$$\text{In air} \quad \frac{1}{C_{\text{TOTAL}}} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_4}$$

The values calculated for C_1 , C_2 , C_3 and C_4 can be used to calculate the maximum permissible current, either related to the cable used or to the submarine conditions. The following section examines these calculations.

3.3 THERMAL CONDUCTIVITY AND CURRENT RATING (8)

3.3.1 CABLE IMMERSSED IN SEAWATER

Working from the equation

$$P = C_{TOT} \cdot \theta_{TOT}.$$

and neglecting the dielectric loss

$$\text{Conductor Loss } (1.08 + \lambda) = \left(\frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}\right) (T_{max} - T_{seawater})$$

$$n \cdot I^2 R_{DC} (1 + A_1 + A_2) (1.08 + \lambda) = \left(\frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}\right) (T_{max} - T_{seawater})$$

$$I_{max/phase} = \left[\frac{\left(\frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}\right) (T_{max} - T_{seawater})}{R_{DC} \cdot n \cdot \left(1 + \frac{A_1}{R_{DC}} + \frac{A_2}{R_{DC}}\right) (1.08 + \lambda)} \right]^{\frac{1}{2}} \quad (3.3a)$$

3.3.2 CABLE IN AIR

Following a similar argument

$$\text{Conductor Loss } (1.08 + \lambda) = \left(\frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_4}\right) (T_{max} - T_{air})$$

$$n \cdot I^2 \cdot R_{DC} (1 + A_1 + A_2) (1.08 + \lambda) = \left(\frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}\right) (T_{max} - T_{air})$$

$$I_{max/phase} = \left[\frac{\left(\frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_4}\right) (T_{max} - T_{air})}{R_{DC} \cdot n \left(1 + \frac{A_1}{R_{DC}} + \frac{A_2}{R_{DC}}\right) (1.08 + \lambda)} \right]^{\frac{1}{2}} \quad (3.3b)$$

The expressions for the maximum current in the power cable in air and seawater can be used to relate the capacity of cables required for submersion to the submarine conditions. The capacity of cables required for the shore ends can also be related to the shore end conditions.

Finally, the amount by which the submarine cable can be up-rated can be related to the submarine conditions. The following sections analyse these cases for a required current flow. These calculations can be applied to any proposed interconnection where the required power flow is known.

3.3.3 CURRENT CARRYING CAPACITY OF SUBMARINE SECTION

If a situation exists where an isolated load is separated by water which has at least approximately known characteristics and properties, the following calculation may be applied. Derivation of formulae used can be found in previous sections. The cable lying on the seabed is shown in Figure 17 on page 48.

<u>The data required is</u> (for unit length of cable)	Typical Value	
Average Temperature of Seawater ($^{\circ}\text{C}$)	T_{seawater}	15
Maximum conductor Temperature ($^{\circ}\text{C}$)	T_{max} usually	75
Diameter of insulation (m)	D_i	0.0748
Diameter of conductor (m)	d	0.005
Thermal Conductivity of Insulation ($\frac{\text{W}}{\text{m}^{\circ}\text{C}}$)	K	0.2×10^{-3}
Diameter of Sheath (m)	d_s	0.072
Thickness of armour (m)	t	0.006
Thermal Conductivity of Seawater ($\frac{\text{W}}{\text{m}^{\circ}\text{C}}$)	C_{sea}	1.42
Depth of Cable (m)	L	30
Conductor c.s.a. (m^2)	a	$70 \cdot 10^{-6}$
Electrical Conductivity of conductor ($\frac{1}{\Omega\text{m}}$)	(copper)	$1.73 \cdot 10^{-8}$
Frequency of operation (rad/sec)	ω	100π
Spacing of Conductors (m)	s	0.052
No. of Conductors	n	3
Sheath Conductivity ($\frac{1}{\Omega\text{m}}$)	σ_s	$1.5 \cdot 10^{-8}$

Axial Distance of each Conductor from centre of cable (m)	d_a	0.025
Conductor separation (m)	C	0.025
D.C. Conductance ($\frac{1}{\Omega m}$)	P_c	3.73×10^3
Diameter of cable (m)	D_c	0.098
Rated voltage (kV)	V	33

The thermal conductances can be calculated

$$C_1 = \frac{2\pi}{K} \frac{1}{\log_e(Di/d)} = \frac{2\pi}{5.5} \frac{1}{\log_e\left(\frac{0.0748}{0.005}\right)} = 0.42 \frac{W}{^\circ C}$$

$$C_2 = \frac{2\pi}{K} \frac{1}{\log_e\left(\frac{D_c + D_s + t}{D_c + D_s - t}\right)} = 7.9 \frac{W}{^\circ C}$$

$$\begin{aligned} C_3 &= 2\pi C_{sea} \frac{1}{\log_e\left(\frac{2L - r_e}{r_e}\right)} \\ &= 2\pi 1.42 \frac{1}{\log_e\left(\frac{2.30 - 0.0049}{0.0049}\right)} \\ &= \underline{2.3} \frac{W}{^\circ C} \end{aligned}$$

A_1 and A_2 could have been calculated, but for a typical 33 kV cable. The A.C. resistance at $20^\circ C$ is quoted as $0.32 \Omega/Km$ (2). Thus $\left(\frac{A_1 + A_2}{R_{DC}}\right)$ becomes $\frac{0.32}{1000} \Omega/m$, division by the d.c. resistance/m allows the resistance to be used in the equation, rather than a constant multiplication factor.

$$\begin{aligned} \lambda &= \frac{16}{5} \frac{G_{CONDUCTOR}}{G_{SHEATH}} \frac{m^2}{1 + m^2} \frac{C^2}{r_{SHEATH}^2} & m &\approx 0 \\ & & G_{CONDUCTOR} &\approx G_{SHEATH} \\ &= \frac{16}{5} \frac{(0.025)^2}{(0.0478)^2} = \frac{16}{5} \frac{1}{4} = 0.8 \end{aligned}$$

$$I_{max} = \left[\frac{(0.42 + \frac{1}{7.9} + \frac{1}{2.3})60}{3(1 + \frac{0.32}{0.268}) \cdot 0.268 \cdot 10^{-3} (1.08 + 0.8)} \right]^{\frac{1}{2}}$$

$$= \left[\frac{60(0.34) \cdot 10^3}{3(2.2)1.88 \cdot 0.268} \right]^{\frac{1}{2}}$$

$$I_{max/phase} = 80 \text{ A}$$

3.3.4 CURRENT CARRYING CAPACITY OF SHORE ENDS

The cable treated in the previous section will not be submerged completely at the shore ends. The cable may be buried, but for the purposes of this dissertation the worst case condition is chosen. The cable is assumed to lie on a flat sandy beach in strong sunlight.

$$I_{max} = \left[\frac{(C_1 + C_2 + C_4)(T_{max} - T_{air})}{R_{DC} n(1 + A_1 + A_2)(1.08 + \lambda)} \right]^{\frac{1}{2}}$$

Additional information required.

- Temperature of Air (°C)
- ↓
- Convection Constant $\frac{W}{m^2 \cdot ^\circ C}$

(3.2e) Allows calculation of C_4 by solving for θ_s

$$(1 + \lambda)(\theta - \theta_s)(\frac{1}{C_1} + \frac{1}{C_2})^{-1} = \pi d_e h \theta_s^{5/4}$$

$$[1.88] [(T_{max} - T_{air}) - (T_{surface} - T_{air})](1.27 + \frac{1}{58})^{-1} = \pi \cdot 0.094 \cdot 2.8 \theta_s^{5/4}$$

Solving for $T_{surface}$

$$T_{surface} = 50.5^\circ C$$

$$\theta_s = 5.5^\circ C$$

$$C_4 = \pi d_e h \theta_s^{\frac{1}{4}} = 3.14 \cdot 0.094 \cdot 0.028 \cdot 1.57$$

$$= 0.68 \frac{W}{^{\circ}C}$$

$$I_{\max/\text{phase}} = \left[\frac{\frac{1}{(0.422 + 7.88 + 0.68)} \cdot 30}{3 (2.2) 1.88 \cdot 0.268 \cdot 10^{-3}} \right]^{\frac{1}{2}}$$

$$I_{\max/\text{phase}} = 50 \text{ A for exposed shore ends.}$$

3.3.5 CABLE BURIED AT SHORE ENDS

If the cables are buried into dry sand to a depth of 0.8 m, the above calculation is modified.

$$C_{\text{ground}} = 0.533 \frac{W}{m^{\circ}C}$$

$$I_{\max} = \left[\frac{\frac{1}{(0.422 + 7.88 + 1.08)} \cdot 50}{3 (2.2) 1.88 \cdot 0.268 \cdot 10^{-3}} \right]^{\frac{1}{2}}$$

$$I_{\max/\text{phase}} = 65 \text{ A}$$

3.3.6 RELATION BETWEEN SUBMARINE CABLE RATING AND SHORE END RATING

In the previous two sections the calculations have shown that for a particular 33 kV cable the submarine section will be able to carry 80 A/phase compared with 50 A/phase at the shore ends. In order that the shore ends be operating safely the maximum continuous current through the cable must not exceed 150 A. In this case the submarine section would be operating at 68% of its capacity. This fraction can be increased in two ways. The shore ends can be dug into a trench in the beach. Based on dry sandy soil, if the cable is dug into a 0.8 m deep trench the capacity of the shore ends increases to 145 A. The submarine cable can

now operate at 80% of its capacity. This fraction can be increased further by using smaller conductor areas in the submarine section, ensuring the joints are below the low water level. The variation of conductor cross sectional areas is plotted against the fraction of cable rating used in the submarine section, in Figure 11 on page 34. The effect of burying the shore ends is obvious. Burying the shore ends allows the submarine section to transmit 1.3 times as much power.

In order to maximise the service rating/maximum rating ratio for the submarine section the submarine cable conductor area should be 0.8 of the area of the shore ends. The conductor radii should thus be in ratio $1.0/0.617 = 1.6$. These figures assume that the other dimensions of the cable do not differ significantly.

3.3.7 FACTORS INFLUENCING DESIGN CHOICE IN SELECTION OF ROUTE

The calculations carried out in sections 3.1 - 3.3 indicate that the important electrical factors are:

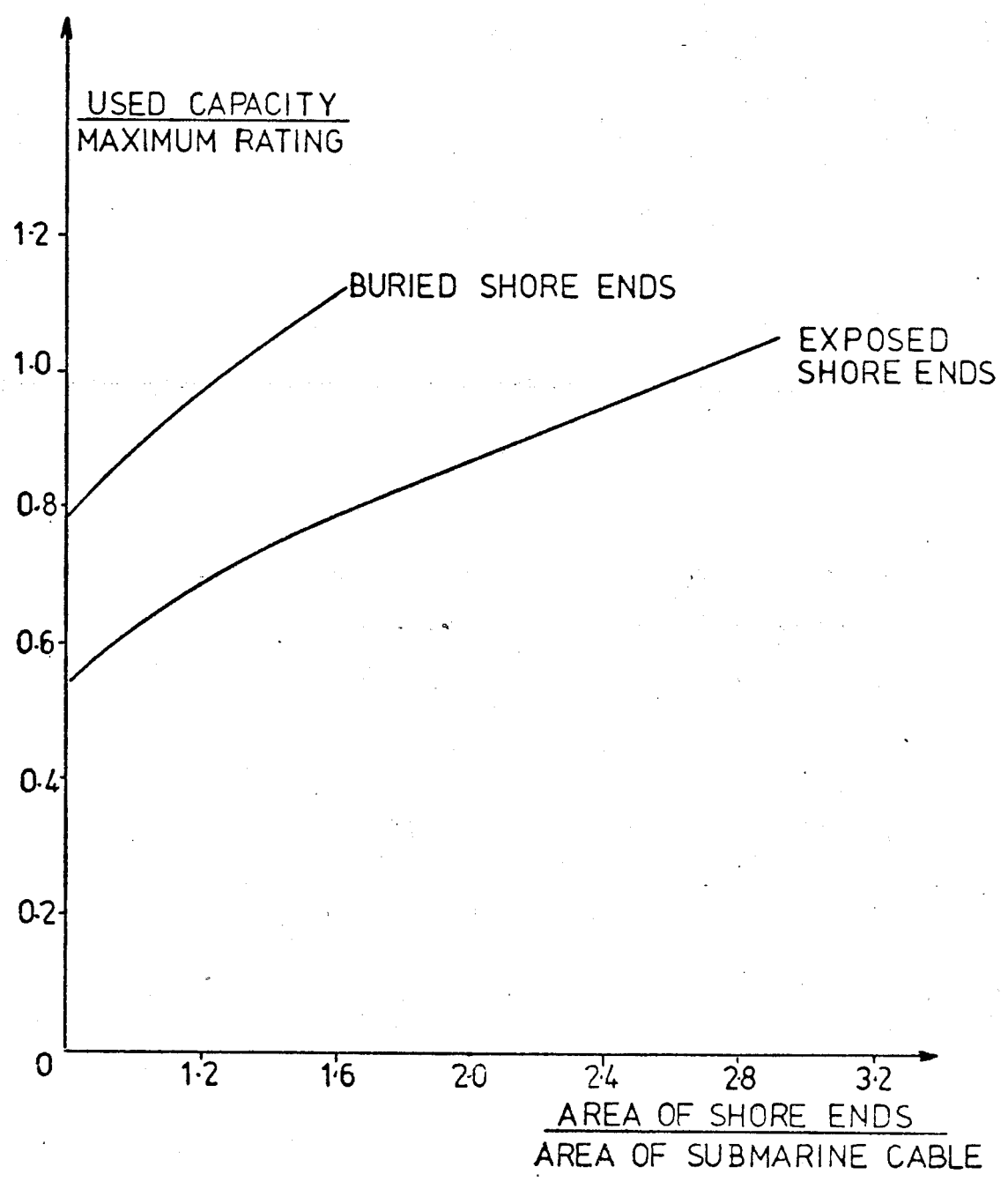
- D.C. resistance/m of conductors in cable, Charging current/m
- Diameter of cable and diameter of conductors,
- Required power flow.

The important geographical factors are

- Proposed average depth of crossing
- Temperature, thermal conductivity of water
- Temperature, thermal conductivity of sand at shore ends
- Type of bottom along route

The landing points should be chosen so that the cable can be buried into

FIGURE 11 VARIATION OF FRACTIONAL RATING
WITH RATIO OF c.s.areas



as highly thermally conducting sand as possible, because this will determine the maximum power flow for a given cable rating.

The submarine route should be chosen so that the cable does not sink into the bottom. This also affects the tendency of the cable to move on the sea bottom, it is assumed that the cable does not move. If the cable sinks into the sand or is buried to prevent motion, the sand dries around the cable and the thermal conductivity of the sand surrounding the cable falls from that of the sea to a value nearer that of the sand at the landing points. The overrating of the submarine section will be affected by whether or not the cable is buried in the seabed. The overrating will have a maximum of 1.61 (conductor area) and will decrease from that value as the cable sinks further into the bottom and dries the sand.

When the thermal dissipation at the shore ends has been estimated the maximum power transfer can be calculated from the current capacity of the shore ends. The required power transfer can therefore be used to estimate the number of cables required for the crossing. The charging current for a proposed cable must be taken into account. The reactive power flow detracts from the maximum power transfer.

$$I_{TOTAL} = (I_{real}^2 + I_{reactive}^2)^{\frac{1}{2}}$$

The maximum current contributing to flow of power becomes

$$I_{real} = (I_{TOTAL}^2 - I_{reactive}^2)^{\frac{1}{2}}$$

The power flow through the link becomes

$$P = 3V_{PHASE-NEUTRAL} \cdot I_{real} = \sqrt{3}V I_{real}$$

The number of cables required can be estimated from

$$P_{\text{required}} = n \cdot P/\text{cable} = \frac{n V}{\sqrt{3}} I_{\text{real}}$$

$$n = \frac{P_{\text{required}}}{V \cdot I_{\text{real}} \sqrt{3}} \quad (3.3c)$$

CHAPTER 4

4. VARIATION IN WATER PRESSURE ALONG PROPOSED ROUTE

Some consideration must be given to the static water pressure at the sea bottom, where a cable installation is being contemplated. If a solid cable is to be installed, the variation in pressure along a proposed route is unimportant, since the solid cable will not be affected by ingress of water other than at underwater joints. Installation of gas filled cables or oil filled pressure cables requires careful consideration of the maximum pressure along a route. The pressure differential must always be maintained slightly positive between the cable and surrounding water for two reasons. The first is that under normal operating conditions the armouring of the cable is not subjected to excessive compressive stresses. The second reason is that in the event of insulation failure ingress of water is prevented and the faults can be located easily by examining the water surface for oil or gas bubbles.

4.1 WATER PRESSURE AND DEPTH PROFILE

To a first approximation the surface of the sea can be taken as an isobaric surface at atmospheric pressure. In this study it is assumed that the land cables are all externally at atmospheric pressure. The external pressure therefore increases from atmospheric pressure to a value dependent on the depth of the cable. The internal pressure will be much greater than atmospheric on dry land, decreasing slightly due to pressure drop along the cable. At the deepest part of the cable route the internal pressure is still very much greater than atmospheric, but just greater than the external pressure. The variation of static external pressure, static internal pressure and pressure differential with

the depth profile of a submarine route is shown in Figure 12 on page 40.

The pressure external to the cable can be expressed as $P_{\text{STATIC EXT}} = \rho g d$
 d - depth (m) g - (9.81 m/s²) ρ - density of water P_A - 105 Nm⁻²

The internal pressure in the cable can be expressed

$$P_{\text{STATIC INT}} = P_A + P_{\text{INT}} (1 - \gamma \ell)$$

ℓ - length from pumping station (m) γ - pressure drop factor
 = 0 in static case.

The pressure differential becomes

$$dP = P_A + P_{\text{INT}} (1 - \gamma \ell) - (P_A + \rho g d)$$

$$dP = P_{\text{INT}} (1 - \gamma \ell) - \rho g d \quad (4.1a)$$

The criterion for correct operation is that nowhere along the cable route showed dP fall below a specified value, and should never be negative. In the static case $\gamma = 0$ and $dP = P_{\text{INT}} - \rho g d$. Where the cables are pumped internally to cool them the value of γ increases with the pumping velocity and density of coolant. In this study it is assumed that the cables are either gas or oil filled and that no intentional motion of the gas or oil takes place.

As the power flow in the cable changes the internal temperatures change. Expansion and contraction of the gas or oil ducts takes place, causing increases or decreases of the pressure differential. Allowance must be made in the design of the pressure system for the condition where the cable has been running at maximum permissible overload for the maximum length of time and the internal pressure is at its highest. On switching off load the pressure differential must therefore decrease. To

allow for this the static internal pressure is raised to a predetermined value, as mentioned previously.

4.2 TRANSIENT VARIATION OF PRESSURE WITH LOAD

The internal temperature in the cable can be calculated if the cable current is known, as in the previous chapter. The temperature distribution at maximum permissible load can be used to calculate the change in gas or oil pressure within the cable. At normal current levels the distribution of excess pressure should be flat, as shown in Figure 13 on page 40, corresponding to the steady state situation, where the heat generated heats the gas or oil and a normal working temperature and pressure is established. Coming off load results in decrease in temperature and pressure as in Figure 14 on page 40. These changes in pressure should occur about a sufficiently high working pressure so that negative pressure differentials never exist. The pressure variations discussed should only be transient provided good pressure regulating equipment is installed in the system.

The changes in pressure can be approximated to by use of the ideal Gas Law.

$P.Vol. = nRT$ (4.2a)

$$dP = \frac{1}{Vol} nRdT$$

$$= \left(\frac{mass.R.}{V.Molecular\ Wt} \right) dT$$

$$= \left(\frac{Density.R}{Molecular\ Wt} \right) dT$$

$$dP = \left(\frac{\rho_g.R}{Mol.Wt} \right) dT$$

- P Pressure N/m²
- V Volume of Gas/Oil in Cable
- R Ideal Gas Constant KJ/kg
- T absolute temperature K
- n no. of moles of gas
= $\frac{mass.}{Molecular\ Wt}$
- ρ_g density of gas

e.g. with a 66 kV Nitrogen Filled cable where the offload and on load temperature difference is 60°C

FIGURE 12 DEPTH AND PRESSURE PROFILES OF
A CABLE CROSSING

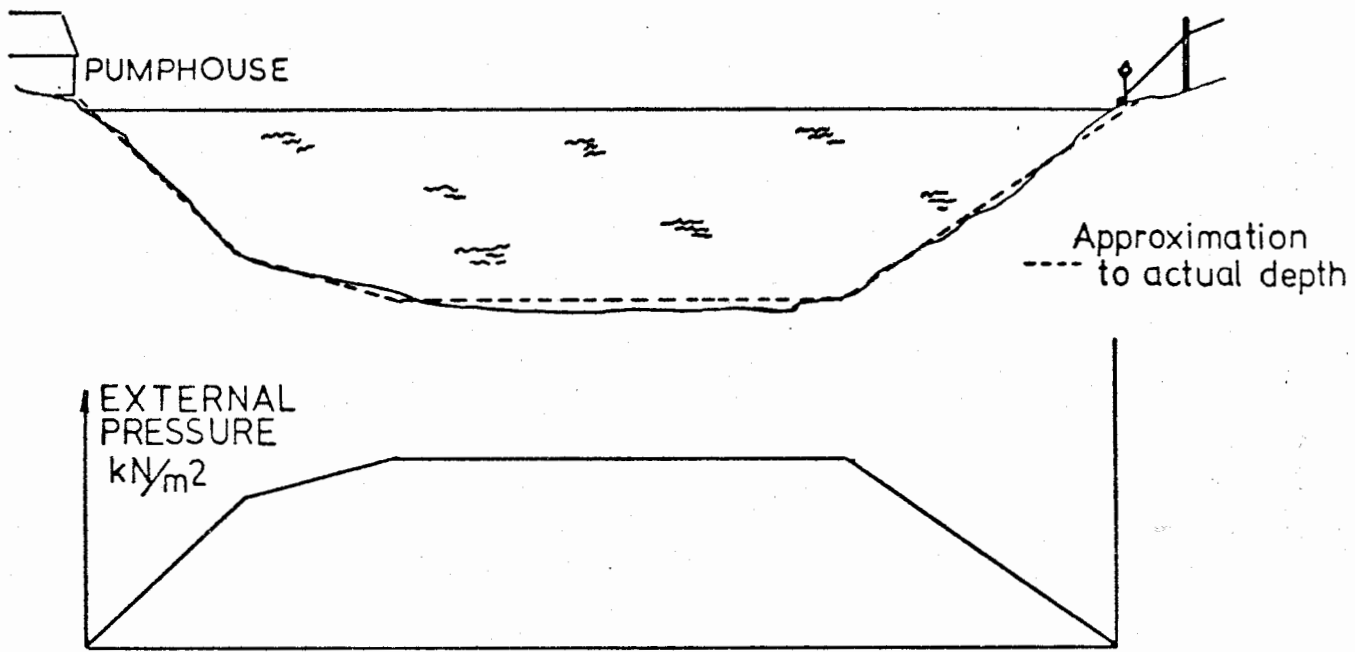


FIGURE 13 VARIATION OF INTERNAL PRESSURE

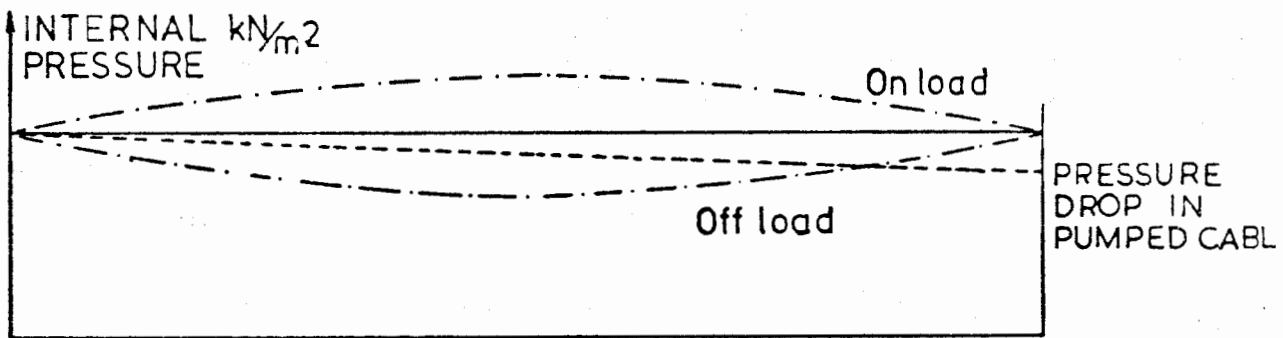
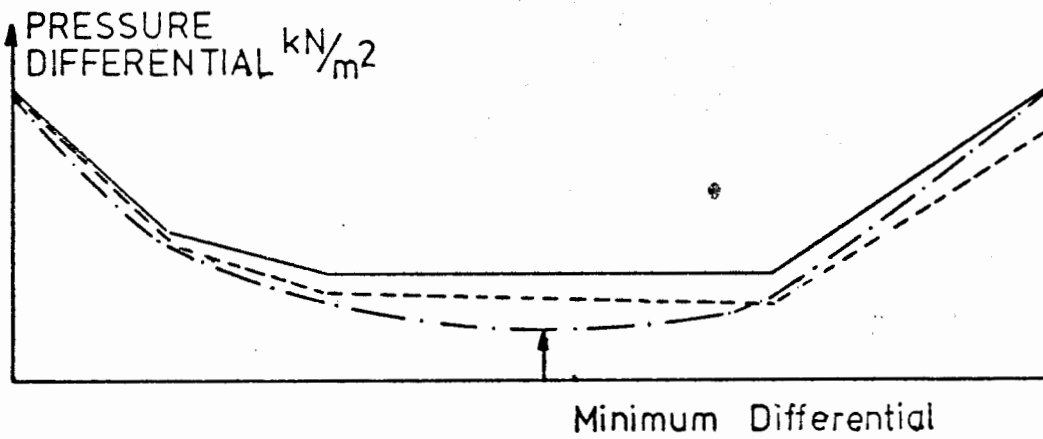


FIGURE 14 VARIATION OF PRESSURE DIFFERENTIAL



Gram Molecular Wt of N₂ occupies 22.4 litres

$$dP = \frac{(\rho \cdot 8.314)60}{28}$$

$$= \frac{1.25 \cdot 8.314 \cdot 60}{28} \text{ kN/m}^2$$

$$= 22.26 \text{ kN/m}^2$$

$$\rho = \frac{28}{22.4 \cdot 10^{-3}}$$

$$= 1.25 \cdot 10^3$$

The minimum pressure differential in steady state should therefore be kept greater than 12 kN/m² or 0.12 atmospheres.

For an oil filled cable, the change in volume during such a heat cycle would be typically 5%. If the system is regarded as closed or constant, that is, that no oil flow takes place from the pump house until the internal pressure falls below a dangerous level, the hot to cold pressure differential can be calculated.

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$$

therefore

$$P_2 = \frac{T_2}{T_1} \frac{P_1 V_1}{V_2} = \frac{343}{283} \frac{100}{105} P_1$$

$$P_2/P_1 = 1.154 \quad \Delta P = 0.154 P_{\text{COLD}}$$

This means that the minimum pressure differential in an oil filled cable must be maintained above 0.077 of the working oil pressure in the cable, to avoid negative pressure differentials on coming off load.

4.3 FACTORS INFLUENCING DESIGN CHOICE IN SELECTION OF CABLES AND ROUTES

The calculations in the previous section show that the important electrical factors are

Required power flow and maximum variation of cable temperatures for calculated dissipation and seabed conditions.

The important geographical factors are

Maximum depth in route/s chosen.

Length of cable required in each route.

Seabed temperatures.

When the required power flow has been decided the seabed temperatures and thermal conductivities can be used to choose the route providing maximum dissipation of heat, as discussed in Chapter 3. The maximum conductor temperatures can be calculated for each route. The route providing the minimum full load temperature will require least additional pressure in the cable to maintain a positive pressure differential if load is lost. The maximum depth along this route can be used to determine the minimum internal pressure required, should impregnated cables be installed. The no load temperature variation can be used to calculate the pressure decrease for both gas filled and oil filled cables on coming off load. Addition of the minimum internal pressure found previously and the maximum pressure decrease should give the minimum working pressure required to maintain a positive pressure differential. The pressure found in this way may be used as a deciding factor in the choice of which type of cables to install, solid, gas-filled or oil-filled. If the required gas or oil pressures were so high that the pumping equipment currently available could not provide such pressures, solid cable may be a better alternative.

CHAPTER 5

5. SEA BED CONDITIONS

The relief of the seabed is usually less rugged than that of dry land due to the absence of erosion by winds and rain. The relief of the seabed tends to lie between being rocky and barren, in deep water to undulating and sedimented in shallow water. The type of bottom onto which a cable is to be laid not only affects the thermal capability of the link, but also can increase the difficulty involved in successfully laying a cable. Should the cable fault, recovery must also be possible, and this must also be related to the relief of the seabed.

5.1 DANGERS TO CABLE DURING LAYING AND RECOVERY

While the cable is being laid a tension must be maintained in the cable to prevent kinking of the cable. Due to the laying of the armouring in cables an instantaneous relaxation in laying tension can allow the armouring to loosen and create voids in the insulation. If an instantaneous increase in tension occurs the armouring may be deformed beyond its elastic limit and on release of the tension the armouring is bent out into a birdcage shape as the cable contracts. During laying therefore the tension in the cable must be kept between limits defined by these conditions.

Two factors make control of this tension more difficult. In all but the calmest of seas, the bowsheaves of the laying vessel will rise and fall with the swell on the water surface. Unless the motion of the vessel is being controlled by anchor winding, as mentioned in Chapter 2, this motion of the brakes on the vessel produces an oscillation in cable

tension about a mean value. The section of cable between the cable sheaves and the seabed will not only be distorted axially by the ship motion, but may be damaged as a result of its being moved by the action of the sub-surface water motion. The second factor which can make laying a cable more difficult is the variation in bottom contour. As the laying depth decreases the payout rate must decrease to maintain an even, positive tension in the cable. If the laying depth suddenly increases the payout rate must be increased to prevent excess tension. A certain maximum will exist in the acceptable amount of change in contour per unit distance of crossing. If the contour of the seabed is so varied that the cable could not be laid undistorted and with no slack the cable would not be safe.

The cable should not be laid onto a seabed which due to its relative fluidity allows the cable to sink deeper than 1 m. If this happens, it is doubtful whether fault recovery of the cable could ever take place. During such a recovery the retrieval tensions required to raise the cable out of 1 m of sediment would damage the armouring irreparably. Section 5.3 analyses the tendency of the cable to sink into a sedimented bottom.

5.2 BOTTOM TYPE AND COMPOSITION

The seabed is classified by the size of particles in the sediment on the bottom (6). The Wentworth classification is shown below.

Classification	Particle Size	Description
MUD	0.0625 mm	Soft Mud, silt or ooze generally providing a smooth soft surface
SAND	0.0625 - 2 mm	From very fine to coarse sand with a generally firm smooth surface
STONES	2 mm - 250 mm	Gravel, Shingle, pebbles, cobble and shell, usually flooring a firm bottom with varying amounts of sand and/or mud.
ROCK	> 256 mm	Rock outcrops, boulders and bed rock, providing a broken and hard bottom.
SAND/MUD	1.0 - 1.5	Generally soft but smooth bottom. Usually found on firm sandy bottom.

Although the sediment is being redistributed continually by sub-surface currents and no exact boundaries can be drawn, submarine areas can be classified by the bottom type. The main area of interest in this dissertation is Western Isles of Scotland. A bottom-type chart is shown in Figure 16 on page 46 . This chart was drawn up by the Ministry of Defence in 1971 (6) and some boundaries may have altered. The type of bottom can affect the safety of the cable. If the bottom is too soft the cable will sink irretrievably. If the bottom is too rough, abrasion of the cable due to movement on the bottom can lead to insulation failure. The next section relates the type of bottom to the possibility of the cable sinking. Chapter 6 analyses the effects of sub-surface currents on the cable and the tendency of the cable to move on the seabed.

5.2.1 SINKING OF CABLES INTO BOTTOM SEDIMENT

Figure 17 on page 48 shows a cross sectional drawing of a cable on the seabed. It is being assumed, for the purpose of the following calculations that the laying of the cable onto the seabed has disturbed

the bottom and embedded the cable slightly.

Consider the cable of radius $R(m)$ is initially sunk $t_0 (m)$ into a seabed of ultimate shear stress $\sigma(N/m^2)$.

The area of seabed in contact with the cable surface/unit length is

$$\frac{\pi R}{180} 2\theta \text{ m}^2 \text{ where } \theta = \sin^{-1} \left(1 - \frac{t_0}{R}\right)$$

The shear force acting parallel to the seabed can be resolved

$$F_x = \frac{2mg\cos\theta\sin\theta}{2} = \frac{mg\sin 2\theta}{2} \quad (\text{for friction})$$

The friction force opposing relative motion of the sediment and cable adds to the (shear stress x area) force.

$$F = \mu R = 2\mu \frac{mg\cos\theta}{2}$$

The incremental area

$$A = \frac{\pi R}{180} 2\theta$$

For the cable to displace sediment and sink, the downward force of the cable through area A must exceed the maximum shear stress of the sediment integrated over the area A . To a first approximation, assume the shear stress is constant over A . The force of the cable tangential to area A must also exceed the static friction force of the cable in contact with the sediment.

Thus

$$2\left(\frac{mg\cos\theta}{2}\right)\sin\theta > \sigma_{\max} \frac{\pi R}{180} 2\theta + 2\mu\left(\frac{mg\cos\theta}{2}\right)$$

solving for $\frac{m}{D}$, such that cable sinks.

$$\frac{m}{D} > \frac{\sigma_{\max} \pi \theta}{(g\cos\theta\sin\theta + \mu g\cos\theta)180}$$

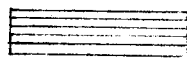
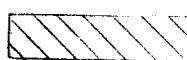
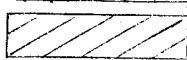
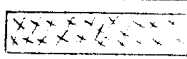
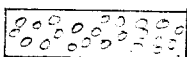
$$\frac{m}{D} > \frac{\sigma_{\max} \pi \theta}{180(\sin\theta - \mu)g\cos\theta}$$

(5.3a)

FIGURE 16

BOTTOM SEDIMENT CHART FOR WESTERN ISLES

KEY

-  Rock
-  Stones
-  Mud
-  Mud/Sand
-  Sand

SHETLAND

ORKNEY



0 10 20 30
16 32 48
MILES/KILOMETRES

FIGURE 17 CABLE ON SEABED

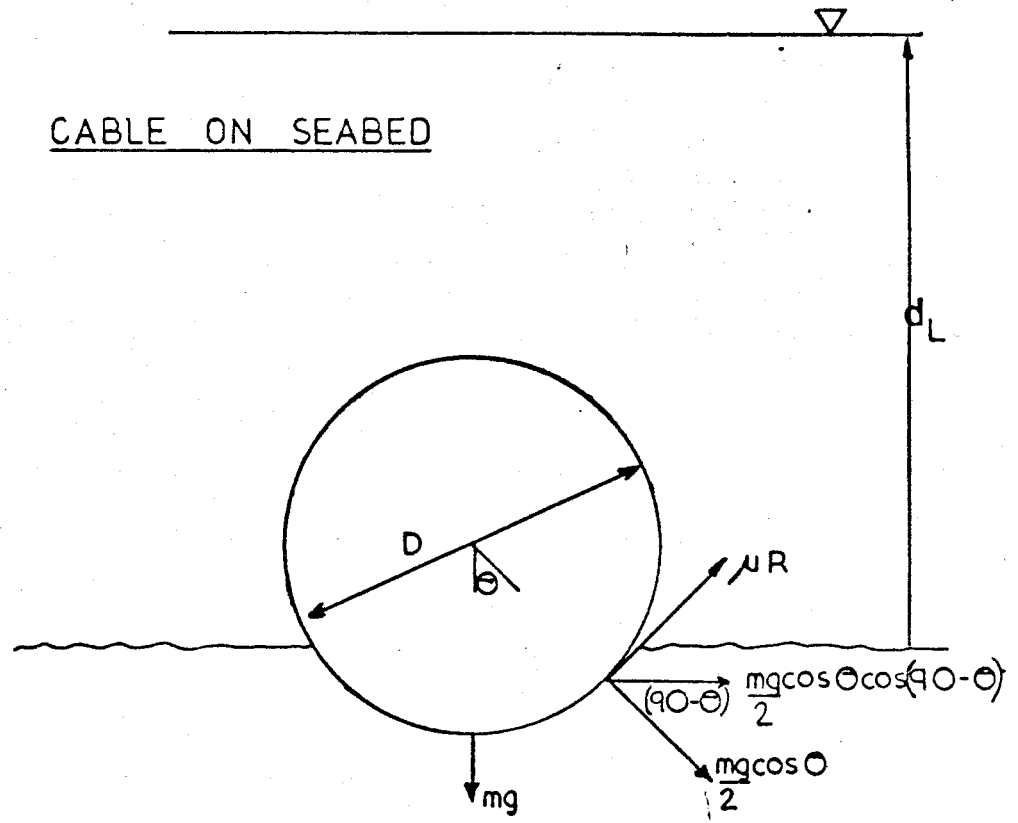
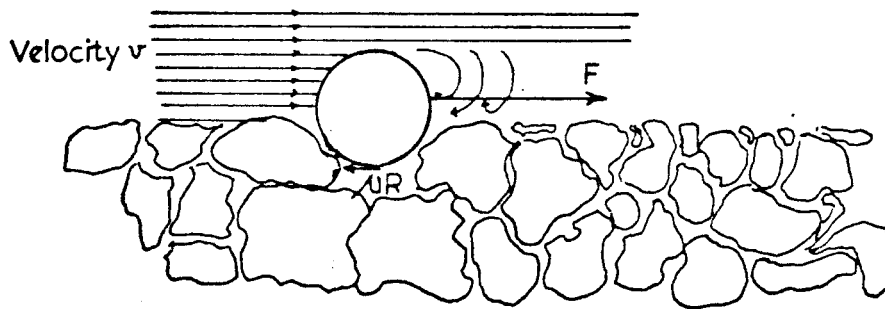


FIGURE 18 FORCES ON SEDIMENT PARTICLE



θ is chosen to be small to estimate the tendency of the cable to begin sinking. As θ increases, i.e. as the cable sinks, the resistance to sinking passes through a minimum and increases again. This suggests it is easier initially, for a cable to sink than it is for the cable to keep sinking. The $\cos\theta$ in the denominator implies the cable cannot sink beyond half its depth ($\theta = 90^\circ$) since at that, infinite resistance would be offered to cable motion. This is due to the assumption that the weight of the cable has no horizontal component. If the sediment is fluid enough to deform continuously under shear stress the redistribution of the sediment around the cable will move the layers of sediment past the axis of the cable and the cable will continue sinking. The coefficient of static friction also exceeds the coefficient of moving friction, therefore the friction force decreases as the cable begins to sink.

It may be a reasonable assumption that if the cable is sufficiently heavy to begin sinking, it will continue to do so past its axis and may embed completely.

The ultimate shear stresses for various sediments where a cable may sink are given below. These figures are taken from a sediment property study in (23)

<u>SEDIMENT</u>	<u>σ_{max}</u>	<u>μ</u>
MUD	< 6.89 kN/m ²	< 0.5
SAND	10.33 - 13.78 kN/m ²	0.666 - 1
SAND/MUD	6.89 - 10.33 kN/m ²	0.5 - 0.666
STONES	> 13.78 kN/m ²	> 1

The coefficient of friction may be estimated. In a complete fluid $\sigma_{max} = 0$ and $\mu = 0$. The coefficient of friction may be taken as 1 where the sediment is just rough enough to prevent relative motion of the cable surface and the sediment. The size of particles is being

estimated as 0.2 of the cable diameter for this to occur. This indicates large stones would be the limiting case for the coefficient of sliding friction. If a straight line relationship is assumed, i.e. $\mu = 1$ for $\sigma > 13.78 \text{ kN/m}$ intermediate coefficients can be calculated. A rock bottom is estimated to have $\mu = 0.5$ by the supply authorities.

Substitution of σ_{max} and μ into equation (5.3a), for θ chosen as 60° [for a cable sunk up to half its depth] gives a relationship between the supportable W/D ratio and the ultimate shear stress of the sediment.

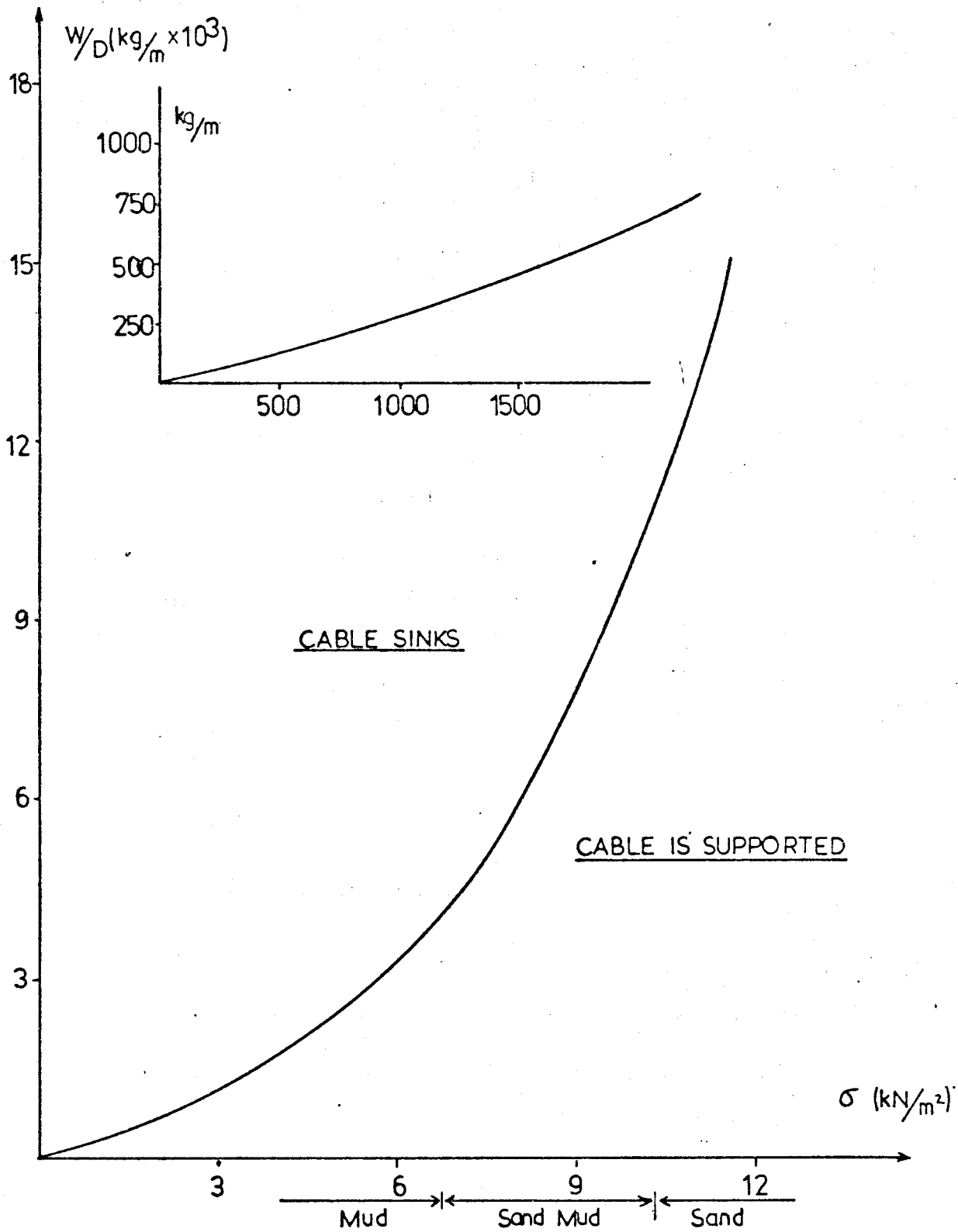
SEDIMENT	m/D_{max}
MUD	< 4019
SAND/MUD	4019 - 11027
SAND	11027 - 29419
STONES	-

The variation of W/D_{max} and σ_{max} is plotted in Figure 19 on page 51. The W/D ratio necessary to sink into sand, say, is almost ten times higher than presently available cable. The lower end of the graph has been enlarged in the inset to bring the scale into that of the W/D ratios available at the present time.

5.2.2 SILTING OVER OF CABLES

Section 5.3.1 showed that for the cable to sink, the bottom sediment would have to be more than 50% (by weight) water. This theory can be questioned by the fact that a sunken galleon of W/D ratio, very much smaller than a 33 kV cable sinks into the bottom sediment. The mechanism which allows sinking into the sediment is scour, or sediment transport (12).

FIGURE 19 SEDIMENT SHEAR STRESS vs. SUPPORTABLE $\frac{W}{D}$ RATIO



The drag force existing between the seabed and the flowing water tends to lower the relative velocity of the water and the bottom. As the particle size, and density of the bottom decreases the relative velocity is decreased partly by deceleration of the water flow to form a boundary layer. The important mechanism is that the sediment becomes suspended in the water and flows in the same direction as the water.

The tendency for the particle to be moved by the flow of water can be analysed.

Assuming spherical sediment particles as shown in Figure 18 on page 48 each with a fraction γ of their surface area exposed to the bottom water flow.

An elemental area dA normal to the water flow will experience a force = Pressure x Area.

$$dF = \frac{1}{2} \rho_{\text{WATER}} v_w^2 dA$$

An element dA , oblique in two dimensions will experience a force

$$dF = \frac{1}{2} \rho_w v_w^2 r^2 d\theta d\phi \cos\theta \cos\phi$$

$$F = \frac{1}{2} \rho v^2 \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} r^2 \cos\theta \cos\phi d\theta d\phi$$

$$= \frac{1}{2} \rho v^2 r^2 4$$

$$= 2 \rho_w v_w^2 r_p^2$$

$$F = 2 \rho v^2 r_p^2 \gamma$$

The frictional restraining force = $\mu R = \mu \frac{\text{Sediment Density}}{\text{Density}} \times \text{volume}$

The particles will become mobile when

$$F > \mu R \quad \text{i.e.} \quad 2\rho_w v^2 r_p^2 \gamma > \mu \rho_p \frac{4}{3} \pi r_p^3$$

$$v^2 > \frac{2\mu \rho_p \pi r_p}{3\gamma \rho_w}, \quad \text{i.e.} \quad v > \left(\frac{2\mu \rho_p \pi r_p}{3\gamma \rho_w} \right)^{\frac{1}{2}} \quad (5.3b)$$

The critical velocity for particle movement can be plotted against the bottom sediment density. γ is estimated at $\frac{1}{3}$. The sediment density, particle size and coefficient of friction are all related and can be changed for each value of sediment density.

SEDIMENT	(m) PARTICLE DIA	μ	(kg/m ³) DENSITY	(m/s) CRITICAL VELOCITY
MUD	< 0.0625 mm	0.006	1249	0.0012
SAND	1.0 - 1.5 mm	0.106 - 0.159	1506 - 1746	0.022 - 0.036
SAND/MUD	0.0625 - 2.0 mm	0.006 - 0.212	1249 - 1506	0.0012 - 0.022
STONES	> 2 mm	> 0.212	> 2003	> 0.051

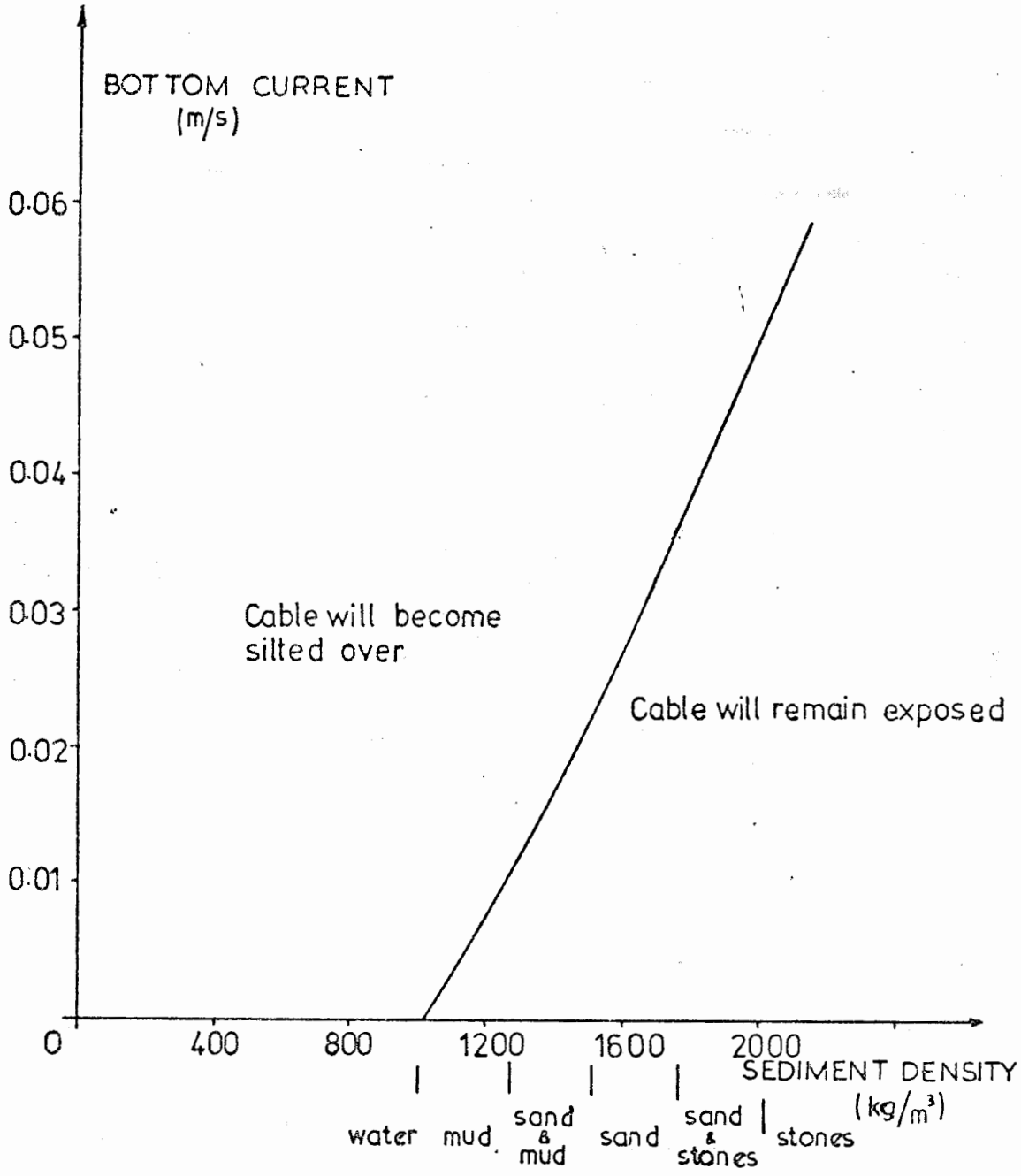
The graph of the variation of critical velocity against sediment density (or bottom type) shows the tendency of the sediment to move in the bottom current. The graph appears in Figure 20 on page 55.

This graph can be used to determine whether or not a cable will become silted over in a particular environment. When the bottom types, or more precisely, bottom densities along a route are known, and the bottom currents are known the density and velocity at each point along a proposed crossing can be plotted on the graph. If the point lies to the left of the critical case, the sediment can move and the cable may become silted over. If the point lies to the right of the line drawn the sediment will remain static and no silting over will take place.

The bottom current can be estimated from the surface currents. Section 6.2 deals with this estimation.

The cable is far more likely to silt over and sink than to sink under its own weight. The important variables for any cable become the sediment density and bottom currents.

FIGURE 20 VARIATION OF SEDIMENT PICK-UP VELOCITY
AND SEDIMENT DENSITY



CHAPTER 6

6. SUB-SURFACE CURRENTS AND FORCE ON CABLES ON SEA BED

The sediment on the seabed is continually in motion. This suggests appreciable currents exist near the seabed. A cable on the seabed will therefore experience a force due to impinging water flow. If this flow is sufficiently fast, or the water sufficiently sediment laden, the force on the cable may be sufficient to produce motion. If the cable moves abrasion of the insulation can lead to insulation failure.

6.1 CURRENT MECHANISMS

There exists three types of currents in the oceans. These currents are generated by different effects and consequently vary in magnitude. The currents are also present in varying proportions, constituting a net current flow. The proportions of these currents in the water is a function of geographical location. The currents also each vary with depth in different manners. The net current at any point in the sea will therefore be a unique function of position, depth, and time. The currents flow with a certain speed in a given direction a more precise representation of the currents would be as water velocities. The current mechanisms, in order of decreasing magnitude are

	Typical Max. Surface Velocity	
Tidal Currents	10 knots	($5 \frac{m}{s}$)
Circulatory Currents	1.2 - 0.6 knots	($0.6 - 0.3 \frac{m}{s}$)
Windstressed Currents	0.06 knots	($0.03 \frac{m}{s}$)

6.1.1 TIDAL CURRENTS

The gravitational forces of the moon and the sun cause diurnal variations in the water distribution on the surface of the earth. The redistribution of the water volume has both horizontal and vertical components. The vertical components give rise to tidal rise and fall. The horizontal components give rise to large scale tidal transport of the seawater. The tidal motions give rise to three types of tidal currents

- (a) Rotary Type - Currents in open sea and along seaboards
- (b) Reversing Type - Occur in inland bodies of water such as estuaries
- (c) Hydraulic Type - Occur in confined areas such as straits.

Clearly the two tidal currents of prime interest in examining a submarine cable route are the reversing and hydraulic type. The currents in confined estuaries, sounds, channels and straits can be considerably greater than the offshore tidal currents due to the reduced area and constant volume flow rate. Prediction of tidal currents in a channel at the design stage may be difficult. A conservative rule might be to examine the nearest recorded open channel tidal current measurement and regard this as a minimum surface current in the channel. Up to date hydrographic data may yield the currents at specific times of the year. The highest current should always be chosen in design estimations. Figure 21 on page 58 shows the surface and sub-surface currents around the Western Isles of Scotland.

6.1.2 CIRCULATORY CURRENTS

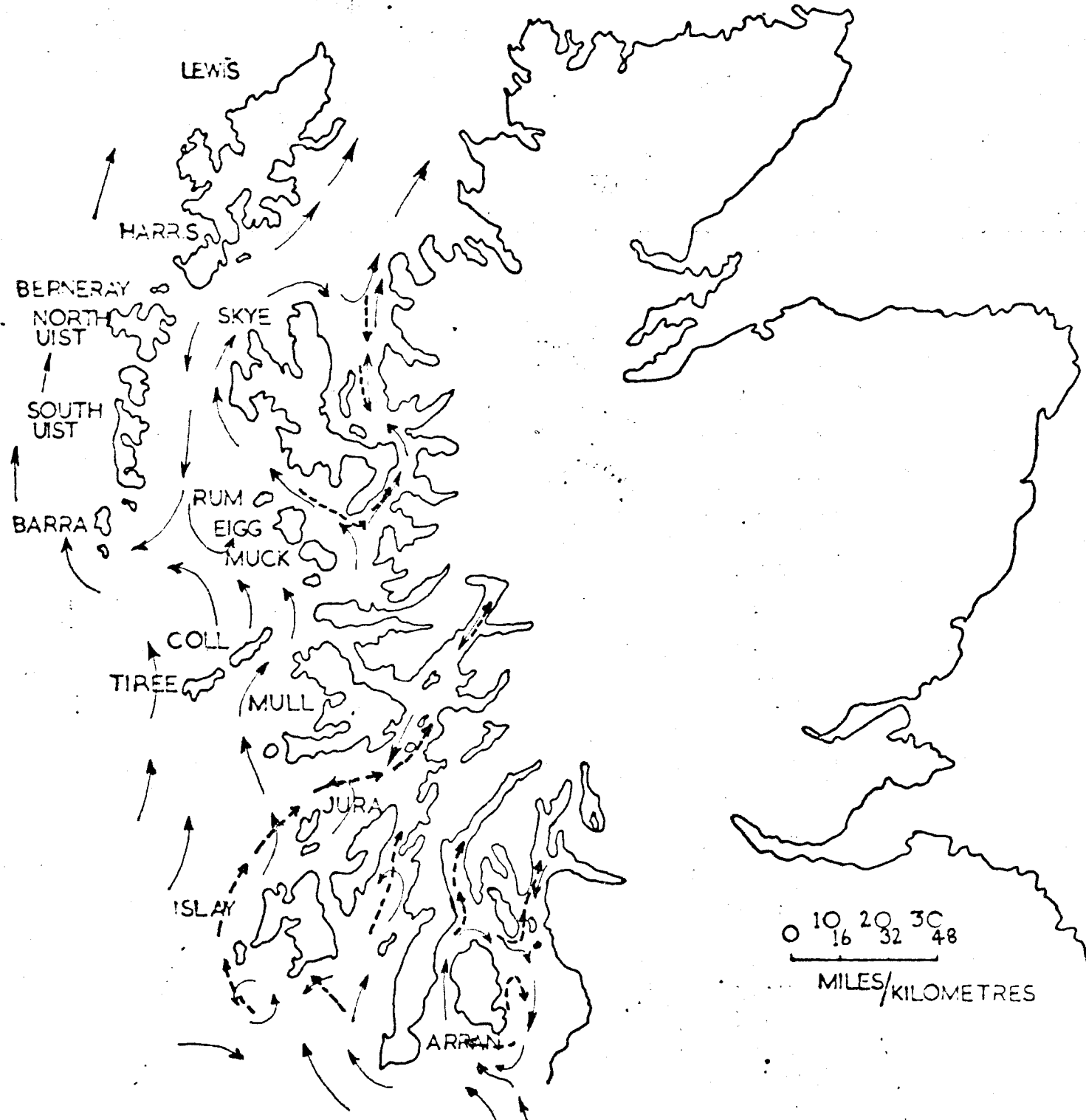
Circulatory currents are open sea currents which added together constitute the major oceanic circulations. The circulatory currents of interest in the choice of a submarine route are eddies and whirls of the

FIGURE 21
SURFACE AND SUB-SURFACE WATER MOVEMENT
AROUND THE WESTERN ISLES - 1971

SHETLAND
 MAINLAND

SURFACE CURRENT ———→
SUB-SURFACE CURRENT - - - - -→
 (Where different)

ORKNEY
 MAINLAND



0 10 20 30
 0 16 32 48
 MILES/KILOMETRES

major oceanic currents. The surface current speeds are generally lower than tidal current speeds. Unless a route is very close to a large expanse of open sea and traverses a narrow strait, the effects of circulatory currents can be neglected in design calculations.

6.1.3 WINDSTRESSED CURRENTS

The relative windspeed at the surface of an expanse of water is zero due to the boundary layer being decelerated to rest by the skin friction of the water. The fluidity of the water allows exchange of kinetic energy in this process. The surface layers of water are accelerated and due to internal friction the lower layers of water are accelerated as a function of depth and surface windspeed. A velocity profile is created as the depth increases. For windstressed currents the velocity vectors lie within a logarithmic spiral about a vertical axis. The magnitudes of these currents are negligible in inshore applications.

Just as the wind and the water surface are at rest relative to one another, the surface current decreases from its surface value to zero at the seabed. A velocity profile exists which describes the variation of water velocity and depth. The currents at cable axis level can be predicted if the velocity gradients and depths of cable are known.

6.2 VELOCITY PROFILES

An analysis of observations of velocities at surface and sub-surface levels (6) suggests a general relationship between surface currents and currents at depths. The highest surface currents occur in tidal streams. The tide generating forces appear to produce streams which have the same direction as the surface currents from the surface to depths of about

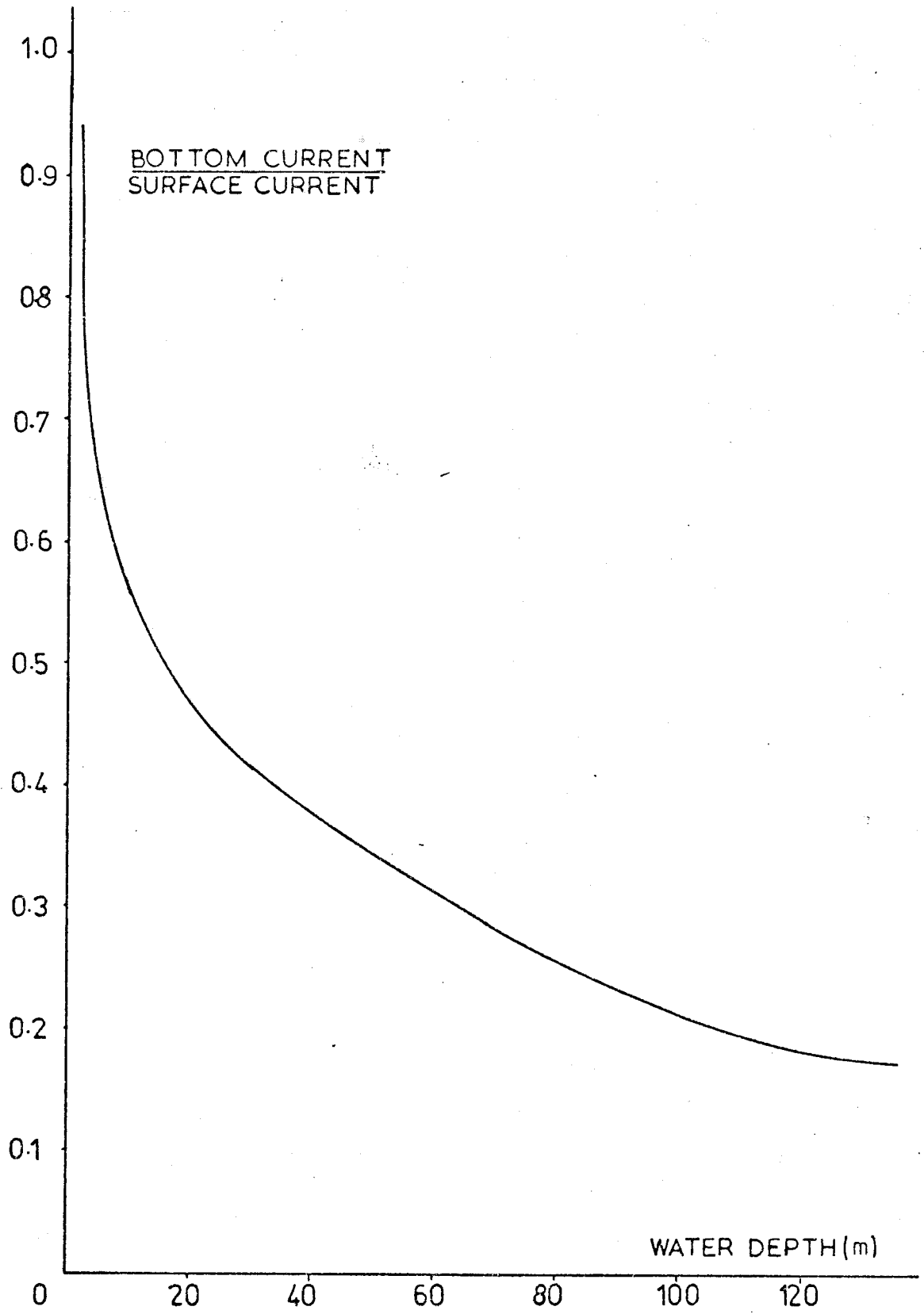
54 m (30 fathoms). As the bottom is neared frictional forces cause a decrease in the velocities. In the open waters around the British Isles a good approximation to the velocity profile is that in waters less than 54 m deep the velocities remain constant from the surface to within 10 m of the bottom. The velocities near the bottom have been found to be on average 0.75 of those at the surface. For depths greater than 55 m the velocity at the bottom has been estimated at 0.5 of that at the surface, although records are scarce.

Boundary layer theory (12) suggests that near the bottom the decelerating water has a logarithmic profile. The boundary layer is being estimated at 0.033 of the total depth. The ratio of the cable radius to the depth of the boundary layer must be expressed as a logarithm to the base ten. The logarithm becomes the exponent of the fraction $\frac{1}{2}$. The raised power fraction relates the velocities above the boundary layer to the velocity at cable axis level. The velocity impinging on the axis of the cable becomes

$$\begin{aligned} \frac{v(d)}{v_{\text{surface}}} &= 0.75(0.5)^{\log_{10}\left(\frac{0.033D}{\text{Cable Dia}}\right)} & (6a) \\ &= 0.75(0.5)^{\log_{10}\left(\frac{0.033D}{0.047}\right)} & \text{for a standard size cable} \end{aligned}$$

The variation of the ratio of the bottom velocity to the surface velocity is plotted against water depth in Figure 22 on page 61. From this graph it is obvious that the shallower the water becomes the higher will be the ratio of bottom/surface current. This means the sections of cable in shallow water at the shore ends will be subjected to greater hydrodynamic forces than those in deep water. In very shallow water the surface current may not be tidal in nature. The tendency for the cable to move and abrade on the seabed is obviously greater in shallow water. The tendency of the cable to move is analysed in the next section.

FIGURE 22 VARIATION OF BOTTOM CURRENT WITH DEPTH
SURFACE CURRENT



6.3 FORCES ACTING ON CABLE ON SEA BED

The resistance to the flow of fluid around an immersed body varies as the square of the fluid velocity, for sufficiently low velocities.

The relationship can be derived from consideration of the fluid pressure on an element dA of cable, as shown in Figure 23 on page 63 .

$$P = \frac{1}{2} \rho_{\text{WATER}} v^2$$

$$dF = C_D P dA = \frac{1}{2} \rho_w v^2 r d\theta dl$$

Resolving horizontally $dF_{\text{horizontal}} = C_D \frac{1}{2} \rho_w v^2 r \cos\theta d\theta$ per unit length

$$\begin{aligned} F_{\text{TOTAL}} &= C_D \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} \frac{1}{2} \rho_w v^2 r \cos\theta d\theta \\ &= \frac{C_D}{2} \rho_w v^2 d \end{aligned}$$

Where C_D is a drag coefficient, normally almost 1.

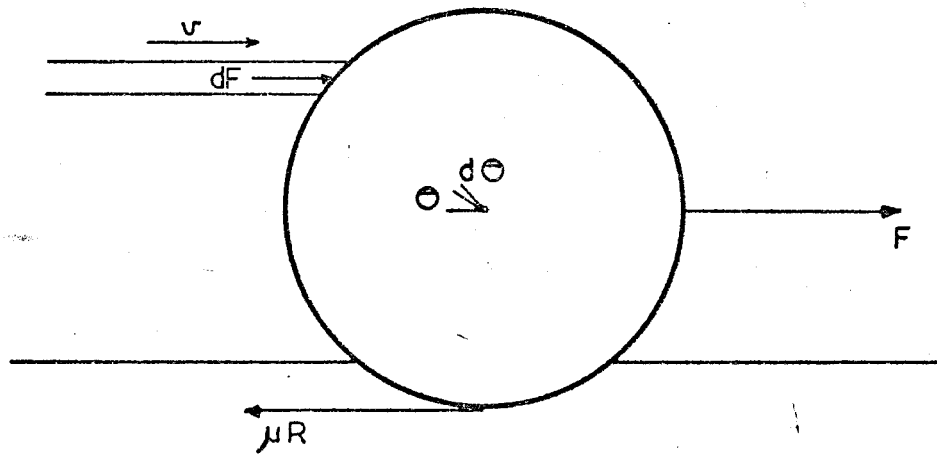
$$F = \frac{1}{2} \rho v^2 d \tag{6b}$$

The frictional restraining force on the cable is simply μR where $R = mg$. If the frictional restraining force is less than the force on the cable due to the water flow the cable will move. The limiting case occurs when the forces are just equal.

$$\frac{1}{2} \rho v^2 d = \mu mg$$

$$v^2 = \left(\frac{2\mu g}{\rho} \right) \frac{m}{d} \tag{6c}$$

Thus the fluid velocity to just produce cable motion can be related to the Weight/Diameter ratio of the cable by the two factors μ and ρ . As the coefficient of friction on the seabed decreases there will be a greater tendency for the cable to move. As the water becomes more sediment laden

FIGURE 23 FORCES ACTING ON CABLE

the force on the cable will increase. The fact that the sediment is in suspension means that the cable may become silted over and the hydrodynamic forces will decrease.

The fluid velocities can be plotted against the weight/diameter ratios which will produce the limiting case, for each value of coefficient of friction encountered on the seabed.

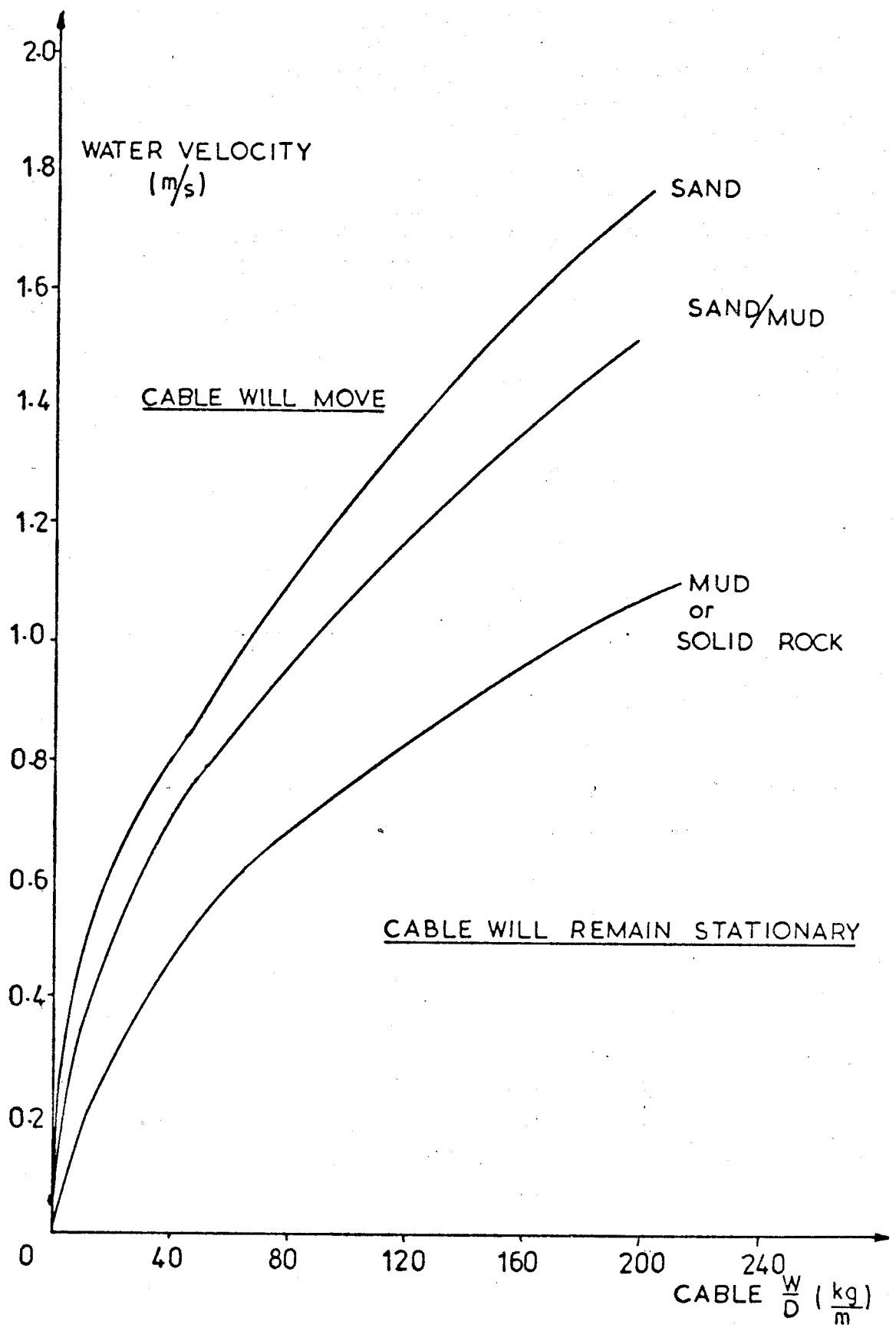
m/d (kg/m)	μ	v in (m/s)
50	0.3 (MUD)	0.54
100	0.3	0.76
150	0.3	0.93
200	0.3	1.08
50	0.6 (MUD/SAND)	0.76
100	0.6	1.08
150	0.6	1.32
200	0.6	1.53
50	0.8 (SAND)	0.88
100	0.8	1.25
150	0.8	1.53
200	0.8	1.77

The graph can be used to determine the tendency of the cable to move. If the surface currents and the water depths along a particular crossing are known Figure 22 on page 66 can be used to determine the velocity at the cable axis. This velocity is plotted against the weight/diameter ratio of the proposed cable. The bottom type defines the limit of static friction and is selected from knowledge of the seabed. If the point defined by W/D and v lies above the line the cable may move. If the point defined lies below the line the cable will remain stationary.

If, for example, an interconnection was to be made across a sandy channel of depth 20 m. A prevailing tidal current had been charted at the surface at 7 knots (3.5 m/s). Graph 22 on page 61 estimates a bottom current of 1.6 m/s. At the shore ends the bottom current may rise to 2.4 m/s. The proposed cable, a 33 kV, 3 core, 70 mm² HSL type has Weight/Diameter ratio 210 kg/m. The section of cable in the deep water would be safe, since the point defined on graph 24 on page 66 lies below the limiting case for a mud bottom. The shore ends, however, are operating in conditions where the point defined lies above the limiting case and may be expected to move on the seabed.

In this case the shore ends of the link may be changed to heavier cable to ensure a higher degree of safety. The thermal rating of the shore ends may also demand that heavier cable be used, and may reinforce this decision. Chapter 7 of this dissertation draws together the design considerations evolved in the previous three chapters and in the latter part analyses some specific cases.

FIGURE 24 LIMITING BOTTOM CURRENT vs. CABLE $\frac{W}{D}$ RATIO



CHAPTER 7

7. SUMMARY OF DESIGN CONSIDERATIONS AND ILLUSTRATIVE EXAMPLES

It has been stressed throughout this dissertation that the considerations made during the course of this study may not always draw out the optimal submarine route between two landbound points. These considerations may be applied to determine the feasibility and security of a submarine link. The chances of producing an optimal route from the design procedure in this dissertation increase with the accuracy and comprehensiveness of the data available. The following sections indicate the type of information required and the likely sources of this information. Relevant equations and figure numbers are also included.

7.1 PRELIMINARY CONSIDERATIONS

The existing mainland grid system and load centre of the isolated community must be identified initially. Flat, sloping, sandy beaches should be chosen as discussed in section 2.1 of this dissertation. Having established several landing points a number of routes can be drawn out on the basis of topographic information. Although not available to the writer of this dissertation a Navy publication (7) has exceptionally detailed and accurate information on the topography and many other aspects of the waters around the British Isles. The routes chosen should traverse the least varying depth. Submarine contour charts are included in (6). The order of merit for the chosen routes may be established by considering the following sections of this chapter.

7.2 THERMAL EFFECTS

Seabed temperatures and compositions must be considered in this section. When the required power flow to the community has been determined the existing grid voltage at the mainland shore end defines the current flow required in the link. If the existing supply is at V_m kV the phase voltage will be $\frac{1}{\sqrt{3}} V_m$ kV. The total current flow can be determined by dividing the required total power by the phase voltage. For three phase cables this current flow will be divided into three phases. The power dissipated in the cable will be three times the heating loss in each conductor. For three phase supply using single phase cables the current flow can be divided into each cable. The power dissipated in each single core cable will be one third of the power in a three phase cable.

The thermal properties of the seabed and shore ends may be used to calculate the maximum current flow in each cable, as shown in section 3.3.3 on page 29. The number of cables required for the required power transfer may be found by dividing the required current flow by the maximum current flow in the link, as defined by the shore ends.

Economy in the number of cables required may be found by choosing landing sites which allow the shore ends to be buried. The fraction of the rating of the submarine cable used may also be increased by correct choice of landing point.

Equations (3.3a) and (3.3b) may be used to calculate the maximum current flow in the link.

7.3 PRESSURE VARIATION

If a pressure cable is to be used for the connection to an island the pressure variation along the route must be considered.

A depth profile of each proposed route is required and in each case the length of cable necessary and maximum depth must be known. The first consideration is to minimise the depth and length of route, subject to equality in other aspects. The minimum pressure differential for each route may be worked out and the required delivery pressure for the gas or oil calculated as in section 4.1. Due care must be taken to ensure that the most severe load transient does not result in negative pressure differentials anywhere along the route (section 4.2). The results of section 4 indicate that the complete loss of supply in a typical gas filled cable results in a 0.1 atmospheres drop in pressure. For a route of maximum depth 20 m the internal pressure of the cable must be maintained above 2.0 atmospheres. For an equivalent oil filled cable the internal pressure must be greater than 2.1 atmospheres.

7.4 BOTTOM COMPOSITION

Chapter 7 showed that the danger to the submarine cable was mainly the possibility of the cable becoming silted over. Only in very wet mud would the heaviest cable sink as a result of settling of the bottom. The pick-up velocity for bottom currents increases as the particle size on the bottom increases. Once the required cable has been identified, the weight to diameter ratio can be determined. The current at the level of the axis of the particles can be calculated. Using equation (6a) the ratio of the seabed and surface velocities can be established. The exponent in 6a becomes the logarithm of, the boundary layer depth divided by the particle radius. The type of seabed can be established by consulting (7) or (6). Using the graph on page 55 the bottom conditions can be plotted. If the point lies to the right of the limiting case, no sediment will be in transport. If the point lies to the left of the limiting case the flow of water on the seabed will be sediment laden.

The increased average density of the flowing water may result in increased hydrodynamic forces acting on the cable.

If a seabed is muddy, the particles will be small. The increased hydrodynamic forces on the cable may be offset by the cable silting over and becoming protected from the flow of water. The cable may sink irretrievably in this case and create thermal problems in operation. If a route is flat and rocky the cable will not sink. If the water is sediment free, flowing at normal density the chances of the cable moving can be estimated normally. A dangerous situation is where a flow of sedimented water impinges on a cable on a flat rocky bottom. Generally, a flat sandy bottom is a good compromise. The cable will not sink irretrievably and will just be located firmly by the bottom sand.

The tendency of the cable to move was analysed in chapter 6.

7.5 MOVEMENT OF CABLES ON THE BOTTOM

The weight to diameter ratio of the cable must be calculated by considering the required power flow and thermal ratings of the environment. The tidal streams for the crossings under consideration must also be isolated and their surface velocities estimated. The depth of the crossings must be considered in three places. At the shore ends and the centre the depths and bottom types must be found by consulting the Navy publication (7). The tidal streams may also be described in this book. Any unusual features on the bottom of a crossing will also be mentioned and must be taken into account.

For each route in concern the bottom currents can be estimated using graph 22 on page 61. The bottom currents may be plotted against the weight to diameter ratio in graph 24 on page 66. Several limiting

cases of cable motion exist depending on the bottom composition. After selecting the appropriate limiting case corresponding to the bottom type of the route the tendency of the cable to move can be estimated. If the point lies to the right of the limiting case the cable will remain fixed in position. If the point lies to the left of the limiting case the cable will move. The cable should either include heavier sections in locations where it may move or should be anchored at intervals. A safer design rule would be that crossings where the cable would move should be avoided.

The considerations drawn together in this chapter should be consistent and applicable to every proposed crossing. Exceptional circumstances may, nevertheless, have to be taken into account.

7.6 ILLUSTRATION OF DESIGN CONSIDERATIONS BY EXAMPLE

7.6.1 SOUTH UIST - BARRA SUBMARINE LINK FAILURE

The first example concerns a fault which occurred in the South Uist - Barra 11 kV submarine cable. The cable is laid in shallow water of maximum depth 20 m and crosses a sand and rock bottom. Tidal surface currents were estimated at 1.5 m/s. The link is shown in Figure 25 on page 73 .

On Monday 8th December 1975 supply to Barra was lost. The cable sheath had become cracked at a distance of 1 km from the South Uist Terminal. The surface tidal currents at the time of failure were recorded at 3 m/s (6 knots). The cracking of the cable was attributed to work hardening of the lead sheath due to motion of the cable on the seabed. Considerable evidence of sediment transport was found.

Using the considerations in Chapter 6 of this dissertation the events that lead to the failure of the cable can be analysed.

For surface currents of 1.5 m/s in a depth of 20 m the bottom velocity can be estimated at 0.47 of the surface velocity from graph 22 on page 61 . The bottom velocity would be 0.7 m/s.

For the cable used the weight/diameter ratio was $\frac{15.5}{0.8} = 195$ kg/m. The bottom type at the fault was rocky outcrop in nature. This defines the lowest limiting case plotted in graph 24 on page 66 .

Plotting the W/D ratio and the bottom water velocity a point below the limiting case is defined. The cable should not have moved under normal circumstances.

The cable motion may have been due to two factors.

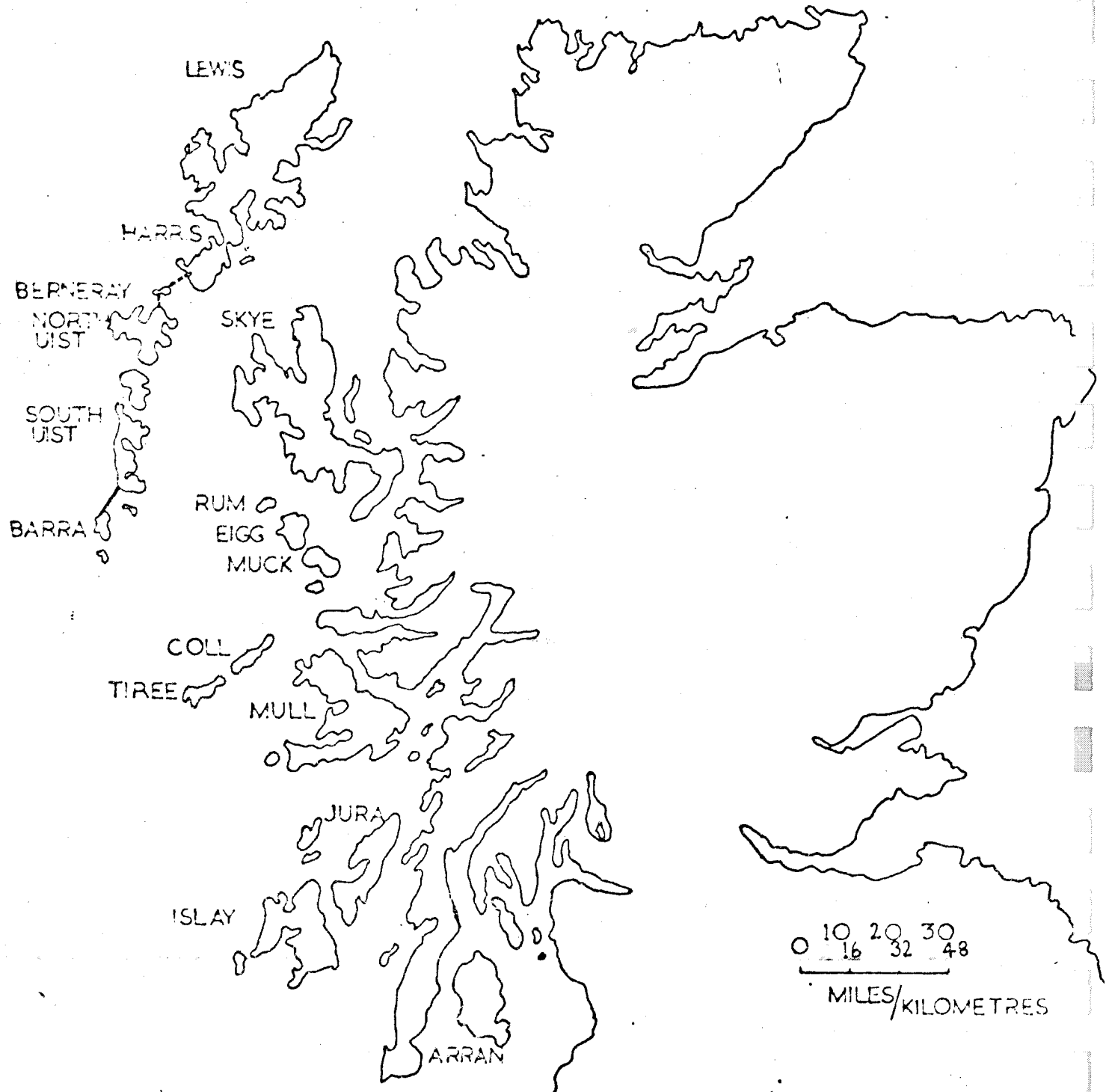
1. The bottom velocities appear sufficiently high to have transported the sand. Graph 20 on page 55 bears this out. Increased fluid density may have caused cable motion in the tidal streams.
2. For surface currents of 3 m/s in a depth of 20 m the bottom velocity can be estimated at 0.47 of the surface velocity. This suggests bottom velocities of 1.4 m/s. Plotting this point on graph 24 defines a point well above the limiting case and the cable should move in this case. This explains the fault occurrence.

This example illustrates the way in which the tendency of the cable to move on the seabed can be checked. It also shows that even designing the route for normal surface currents, excessive currents may occur which may lead to failure.

FIGURE 25 SOUTH UIST - BARRA AND
PROSPECTIVE HARRIS - NORTH UIST
SUBMARINE CABLES

SHETLAND
MAINLAND

ORKNEY
MAINLAND



0 10 20 30
0 16 32 48
MILES/KILOMETRES

7.6.2 PROSPECTIVE HARRIS - NORTH UIST SUBMARINE CABLE

In 1975 a dissertation (15) in the Electrical Engineering Department of Edinburgh University analysed the feasibility of connecting two diesel generating stations in Stornoway and South Uist. The link was to have been 33 kV a.c. double circuit and was to include 16 km of submarine cable. The proposed route is shown in Figure 25 on page 73. This prospective link is an ideal example of submarine power interconnection in the Western Isles of Scotland.

The interconnection may be analysed using chapter 3 - 6 of this dissertation.

1. Thermal Rating. The required power flow to North Uist is estimated at 30 MW. The present installations on Harris are 33 kV double circuit overhead lines. The required current flow in the link must be

$$I_{\text{max phase}} = \frac{30 \cdot 10^6}{33 \cdot \sqrt{3}} = 530 \text{ A}$$

The maximum current flow, limited by the shore ends being buried into sandy beaches can be calculated.

$$I_{\text{max}} = \left[\frac{(\frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3})(T_{\text{max}} - T_{\text{seawater}})}{R_{\text{DC}} n (1 + A_1 + A_2)(1.08 + \lambda)} \right]^{\frac{1}{2}} \quad (3.3a)$$

The constants are listed on page 29 for a 33 kV solid cable

$$C_1 = 0.42 \frac{\text{W}}{\text{°C}} \quad C_2 = 7.9 \frac{\text{W}}{\text{°C}} \quad C_3 = 2.3 \frac{\text{W}}{\text{°C}} \quad \text{for sea}$$

$$A_1 + A_2 = \frac{0.32}{R_{\text{DC}}} = 1.2 \quad \lambda = 0.8 \quad C_4 = 1.1 \frac{\text{W}}{\text{°C}} \quad \text{for sand}$$

R_{DC}/m can be found (2) for HSL cable to be $2.7 \times 10^{-4} \Omega/\text{m}$.

T_{max} and T_{min} for the cable and shore ends can be taken as 75 and 25°C.

For the submarine section $T_{\text{min}} = 15^\circ$.

7

$$\text{The submarine section can carry } 3 \times \left[\frac{60(0.34) 10^3}{3 \cdot 0.268(2.2)1.88} \right]^{\frac{1}{2}} = 240 \text{ A}$$

The charging current is quoted as 1.6 A/km for each conductor.

The charging current can be neglected as it is only 80 A. The decreased amount of current contributing to power flow becomes 226 A.

$$\text{The shore ends can carry } 3 \times \left[\frac{50(0.242) 10^3}{3 \cdot 0.268 \cdot 2.2 \cdot 1.88} \right]^{\frac{1}{2}} = 190 \text{ A}$$

Two points arise from this calculation.

- a. The conductor area of the shore end sections must be increased to fully load the submarine section. From the graph in Figure 11 on page 34 the conductor area must be increased to 1.2 times that of the submarine section. In this case the shore ends could be increased from 70 mm² to 95 mm².
 - b. The submarine link must be nine circuit in order to supply the required power. The required current would be 524 A. Using nine circuit submarine cable, the maximum safe current would be 570 Amps.
2. Pressure Variation. The submarine route is sufficiently short at 16 km and the crossing sufficiently shallow that solid cables would suffice in this case.
 3. Bottom Conditions. Figure 16 on page 46 indicates that the proposed cable would cross a rocky expanse of seabed. No sand or silt appears sufficiently near to bury the cable or increase the hydrodynamic force on the cable. The coefficient of friction can be taken as 0.5 in this case.
 4. Tendency of cable to move on seabed. Records (7) show that the highest currents in the Sound of Harris are 2.5 m/s. The deepest

part of the crossing is 100 m in depth. The shore ends would be in 10 m of water.

The shore ends would have W/D ratio 218 kg/m. The bottom velocities in 10 m of water would be 0.56 of the surface velocity. In this case $0.56 \times 2.5 = 1.4$ m/s. Plotting the W/D ratio against the bottom current the point defined lies above the limiting case and the cable may be expected to move.

In this case the cable could be laid in loops at the shore ends. The transverse force on the cable would be minimised along the length of the cable. The cable could be anchored at the extremities of the loops.

7.6.3 SHAPINSAY-STRONSAY LINK

The power cable connecting Shapinsay and Stronsay in the Orkney Islands was installed in water of charted surface velocity 2 m/s. A 33 kV, 70 mm² HSL cable was used and considered sufficiently heavy to remain without moving in these currents. Examination by a diver during a strong tidal run discovered that the cable was visibly moving back and forth on the seabed. The surface velocities have since been measured at 4 m/s.

The North of Scotland Hydro Electric Board are considering armouring and weighting this cable. With the information given the amount of weighting necessary to immobilise the cable can be calculated.

The cable was found to be moving on a rocky bottom in 34 m of water. For a 4 m/s surface velocity the graph in Figure 22 on page 61 suggests that the water velocity at cable axis level would be $0.44 \times 4 = 1.6$ m/s. On a rock bottom the weight to diameter would have to be increased to 430 kg/m. The weight/m of the cable would have to be increased to 43 kg/m.

An additional 20 kg/m would have to be added to the cable. 200 kg ballast bags of cement could be added every 10 m of cable length. Additional security could be found by increasing the weight of ballast every 10 m or by decreasing the spacing between the ballasts.

CHAPTER 8

8. CONCLUSIONS

As a result of the work carried out in this dissertation several conclusions can be made.

1. The high costs involved in commissioning and repairing submarine power cables stresses the need for accurate design of routes.
2. With the most stringent of designs a high probability of cable failure still exists due to third party damage or due to unpredicted submarine conditions.

The technical considerations in this dissertation have suggested the following features which may be used in designing a cable route:-

3. Due to the high thermal conductivity of seawater a submarine cable section can carry $5 \times$ more power than an exposed section of cable on dry land. The shore end sections of a cable are the limiting sections for the power flow through a submarine link. Burial of the shore ends into wet sand may allow an increase in the power flow. For maximum usage of the capacity of the submarine section the shore end cables should be about 60% greater in cross sectional area.
4. The use of pressure cables does not seem necessary for local interconnections around the coasts of Scotland. On longer, deeper links gas-or oil-filled pressure cables can be used to effect supply.
5. The type of bottom onto which the cable is to be laid must be given careful consideration. There appears to be no danger of the cable sinking into sediment. The hydrodynamic forces acting on sediment particles may be sufficient to transport the sediment from around the cable. If this is the case the cable will sink. If the

cable sinks too far into the sediment it may become irretrievable in the event of a fault.

6. From simple considerations the coefficients of sliding friction on various types of seabed can be estimated. When compared with those obtained experimentally reasonable agreement is found.
7. The velocity profile for tidal streams, discussed in section 6.2 on page 60, agrees well with experience and allows prediction of hydrodynamic forces on cables on the seabed.
8. A maximum surface current exists for every cable laid onto every type of seabed. If the surface current exceeds this value the cable will move on the seabed and abrasion of the armouring will take place. The hydrodynamic forces on a cable are greater in shallow water than in deep water. Because of this the submarine sections tend to move more at the shore ends. In order to prevent such occurrences the weight to diameter ratio of the shore ends must be increased by either using heavier cables or by weighting existing cables.
9. These considerations suggest a series of design rules which can be applied to any link and may increase the security of the link, once installed.

ACKNOWLEDGEMENTS

The writer of this dissertation wishes to record his gratitude to the following people for their help during the course of this dissertation.

Mr. H. Dickinson of the Department of Electrical Engineering for his guidance and assistance.

Messrs. Gove, Cochrane and Greig of the North of Scotland Hydro-Electricity Board for providing valuable information.

Leith Nautical College, for the use of their library.

Mr. C.H.M. Matthews for his photographic work.

Special thanks are also extended to Mrs. H. McKeating for typing this dissertation.

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ADDENDUM

SUBMARINE TRANSMISSION OF WAVEPOWER

The preceding dissertation describes the design constraints applicable when considering submarine cable links. One interesting application of this technology is in the transmission of wave-produced electricity. This addendum considers an illustrative example of a wave-power scheme to show how the rules described in the dissertation should be applied.

Two schemes have been considered which may be used to carry 400 MVA from 20 km offshore to the Western Isles.

- (1) High Voltage A.C./D.C.
- (2) Low Voltage A.C./D.C.

Each scheme can be examined under the following criteria

- (a) Number of cables required to transport power
- (b) Necessity of pressurising cables
- (c) Tendency of cables to move in shallow water.

420 kV A.C. (3 Cable) Link

3 420 kV D.C. (single ϕ) cables could be used to make up a 3 ϕ circuit.

- (a) Required Current Flow

$$\begin{aligned} I/\text{cable} &= \frac{400 \times 10^6}{\sqrt{3} 420 \times 10^3} \\ &= 550 \text{ A} \end{aligned}$$

Maximum Continuous Current

$$I/\text{cable} = 600 \text{ A}$$

Thus the required current flow could be met using a 420 kV, 3 single phase cable connection.

(b) The cables would have to be oil filled and pressurised to around 500 kN/m^2 for submerged depths of 50 m, in order to maintain a positive pressure differential between the cable and the sea bottom

(c) If the depth of the water at the shore ends is known, and the tidal velocity, the bottom current can be predicted from graph 22.

For a 420 kV cable of W/D ratio 310 kg/m to remain stationary on the following bottoms, the bottom velocities must be below

Mud or Solid Rock	1.2 m/s
Sand/Mud	1.8 m/s
Sand	2.1 m/s

The landing points must be chosen to satisfy these conditions. The more likely outcome is that the cable would become silted over (graph 20).

± 250 kV D.C. (2 cable) Link

(a) Required Current Flow

$$\begin{aligned} I/\text{cable} &= \frac{400 \times 10^6}{250 \times 10^3 \times 2} \\ &= 800 \text{ A} \end{aligned}$$

Maximum Continuous Current

$$I/\text{cable} = 500 \text{ A (Ch.3)}$$

Two D.C. Links would thus be required to allow transfer of the required power.

(b) Two alternative types of cable, and hence pressure fluid could be used. Gas filled cables such as those used in the Cook Strait Link could

be used, or Mollerhoj cables could be used. Again a minimum internal pressure of 5 atmospheres would be required.

(c) For a 250 kV cable, the W/D ratio is estimated at 360 kg/m. Thus it is again possible to predict the safety of the cable, if the surface velocity, water depth, and bottom type are known.

If the cable is laid on the following types of bottom, the corresponding maximum currents exist.

Mud or Solid Rock	1.4 m/s
Sand/Mud	2.1 m/s
Sand	2.3 m/s

Again, though, silting over of cables would be a more likely result.

Lower voltage cables can be used, but the effect is to increase the current flow and hence number of cables required. For example, a 33 kV supply of 30 MVA requires nine three phase cables.

It would appear more sensible to lay one or perhaps two links at high voltages, than to have to repeat a laying procedure several times for a low voltage link.